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The 'fast' components of the coupling between the land surface model CABLE and the atmosphere within the Earth system model ACCESS

Project progress report

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

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Important disclaimer

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

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 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.

In its formative stage the project identified two substantive issues (concerning meteorological forcing and time-stepping of the energy balance) within the current implementation of CABLE-UM. This report documents progress towards implementing solutions to these two issues within CABLE and ACCESS. During the development and those solutions, further issues regarding the coupling of CABLE to the UM and, more generally, within the current CABLE code were identified. These are briefly documented here. Solutions for the majority of the identified issues have been devised, implemented, where necessary extended to accommodate other advances to CABLE, and are now being tested by the wider CABLE community. If successful, these will form a substantive set of changes within the next generation of CABLE. Further effort is however needed to fully incorporate solutions to all the identified issues.

Finally, a more extensive review of the formulation of a key component (turbulent exchange) of CABLE is presented. This illustrates that there are significant inconsistencies within that component with, as yet, unknown consequences for the wider performance of CABLE. This has the potential to form a focus for future development and science enhancement of CABLE.

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 a detailed comparison of the role of CABLE within ACCESS (Kowalczyk et al. 2016), 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 UK Met Office's atmospheric model, the Unified Model (UM), were coupled together. No particular type of error was at that point precluded as potentially both technical (i.e. computer code and implementation related) and scientific (e.g. mutually exclusive assumptions) issues could have occurred. A review of 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). These concerned i) the atmospheric forcing used to drive CABLE and ii) the functional form and completeness/sequencing of some of the terms involved in the coupling. Sections 2.1, 2.3 and 2.4 of this report include discussions and status updates on the implementation of three areas of work that, together, address these two issues. During the testing and development of those methods, further issues affecting the 'fast' components of CABLE were identified. Sections 2.2 (conservation of water) and 3 (others) of this report provide discussion of those issues and the progress made towards rectification. For brevity, most of the detail of the implementation of any fixes is left to technical documentation that accompanies those efforts – these technical documents can be found on the CABLE community webpages. Only selected results are shown (demonstrative only); more formal, scientific assessments of these advances remain for future work.

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

Finally, in Section 4, a further review of the representation of turbulent exchange within CABLE is presented. It argued that the current model is internally inconsistent (and somewhat outdated) in its representation of turbulence. A proper investigation of the impacts that such weaknesses may have on model performance is not possible without further effort. Nevertheless, it is clear from the nature of the issues found that the diurnal cycle and the surface energy balance and, correspondingly, the extremes in near-surface climate simulated by CABLE (within and outside of ACCESS) will be affected.

It should be noted that this project is proceeding in parallel with, forms part of, and in some ways has been superseded by, other efforts concerning the coupling of CABLE within ACCESS. In particular

1. The development and benchmarking of the next generation of the ACCESS model, with possible 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.

The work presented here is based upon CABLE 2.2.3. It is anticipated to be included (except where noted) within the version of CABLE to be used within ACCESS-CM2 and a future ESM version. The included changes have been, or are intended to be, incorporated in a consolidated branch (share/vn10.6_CABLE) in preparation for use and testing within ACCESS-CM2.

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

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 dioxide given time-step mean atmospheric forcing as provided by the UM. The UM handles the evolution of the atmospheric boundary-layer and CABLE handles the evolution of the land surface, including soil, vegetation, snow and ice-covered land. CABLE replaces many components of JULES within ACCESS, however the ACCESS co-opts the JULES code for the surface-atmosphere exchange over the sea and sea-ice as well as the JULES river runoff scheme. The following four sub-sections outline concerns with the coupling within ACCESS1.3; Section 2.2 also applies to surface-only simulations.

The underlying cause of each of these issues is that an implicit numerical scheme is used to solve the evolution of the state of the atmospheric boundary layer[2] (Diamantakis et al. 2006, Wood et al. 2007). This imposes a distinct structure on JULES (Best et al. 2011; 2015) and on the use of JULES within the UKMO meteorological and climate models. However this structure is different to how CABLE operates and, consequently, adjustments are required when CABLE operates in ACCESS compared to more conventional, surface-only, uses.

Briefly the differences between the ACCESS-coupled and surface-only configurations of CABLE are that (non-exclusively)

- CABLE is called multiple[3] 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 quantify those turbulent transfer properties (e.g. the turbulent diffusivities) within the UM's boundary-layer scheme that depend (directly or indirectly) on the surface fluxes.
- On subsequent (implicit) calls updated meteorology is used to recalculate the energy balance. The soil-snow states[4] 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.* (See Harman 2016 for further detail on the origin and form of the correction terms).
- The revised surface turbulent fluxes are then used to evolve the boundary-layer.

Section 2.1 considers the meteorological forcing used at each point in the sequencing, Section 2.3 considers the functional form and completeness of the correction terms and Section 2.4 the sequencing of when the correction term is applied to the soil moisture calculations. Section 2.2 raises a significant issue concerning the surface energy balance and soil water balance identified during testing of Section 2.3. The order given here relates to the order of work that eventuated

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[2] i.e. the rates of change are determined by conditions at the end of the time step, both the fluxes and state variables are solved simultaneously.

[3] 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.

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

within the project. Only a brief outline and some demonstrative results are given here, more extensive documentation sits within the Tickets in the CABLE repository.

2.1 The atmospheric forcing of CABLE (Ticket 132)

A key difference between the calls to CABLE within each time step is the meteorology forcing (temperature, humidity and precipitation) used. ACCESS1.3 applies updates to these variables immediately prior to the calculation of the energy balance. These updates originate (numerically) from the UM boundary-layer scheme. Further detail is given with the Ticket where it is shown that

1. the temperature and humidity increments used may not result in physically realisable or realistic meteorological conditions;
2. the temperature and humidity increments used are not necessarily small (as implicitly assumed in the JULES formulation) nor result in meteorological conditions that lie in between the conditions at the start of the time step and the start of the next time step; but that
3. the errors associated with using the inappropriate increments, while producing inconsistent land-atmosphere fluxes, are unlikely to be sufficient to initiate a model crash.

To address this issue alternate, if still approximate, increments need to be evaluated from CABLE and UM working variables and applied to the forcing meteorology.

2.1.1 Implementation

Fixes for this issue (Option 3 in the Ticket documentation) have been developed for use within ACCESS1.3, UM version 8.5 and UM version 10.6 (the UM code for ACCESS-CM2). Developments to the code structure within the UM since ACCESS1.3 necessitate different (but related) methods in each case. This code has been successfully tested within ACCESS 1.3 and UM version 8.5 in AMIP simulations (no results are shown, in monthly averages the differences were found to be small). Delays in the development of a stable, initial base of CABLE coupled to UM version 10.6 have so far prevented implementation, technical and scientific testing within the ACCESS-CM2 model. In each case a small amount of new code is required within the modules that interface CABLE with the UM-JULES and within the cable_implicit_driver module of CABLE. The development has been implemented on a logical switch (l_revised_coupling).

Relatedly, through discussions with the UKMO, consideration is needed around sequencing of the implicit call to CABLE relative to the implicit call to the JULES sea and sea-ice exchange calculations. To maintain the intention of those parts of JULES (that ACCESS is utilising) the call to CABLE should occur earlier. Away from mixed coastal grid cells this issue is irrelevant. A second implementation option has been devised to facilitate the change in sequence. This code has not been tested within any configuration of ACCESS to date. Further discussion with the UKMO, as part of the TILS project, is needed on this issue.

2.2 Moisture conservation in CABLE and ACCESS (Ticket 137)

The conservation of energy and water (liquid+solid) is the primary requirement of any LSM. Numerical precision implies that absolute conservation cannot be obtained – however CABLE as used in ACCESS1.3 demonstrates unsatisfactory lack of water conservation (when using the default soilsnow scheme). After testing and diagnosis, the main underlying reason(s) for the lack of conservation emerged as being inconsistencies around whether the latent heat for evaporation or sublimation is used in different parts of the code. In particular the energy balance code (cable_canopy and cable_cbm which set the latent heat flux) and soil moisture code (cable_soilsnow which evolves the snow pack and soil moisture) were, on occasion, using different values for latent heat of evaporation/sublimation. Four specific cases of usage of mixed values for the latent heats were identified

1. on the evaluation of the correction term to the latent heat flux (Section 2.3)
2. for the deposition of frost
3. for sublimation of thin snow layers
4. with frozen, but uncovered by snow, soils.

A second reason, operating alongside factor 4, for lack of conservation is that CABLE soilsnow does not permit the sublimation of ice from within the soil matrix. To permit a latent heat flux from frozen soils a minimum fraction of soil moisture is retained at all times, however the soil latent heat flux is not restricted to ensure that this minimum value is maintained.

2.2.1 Implementation

A set of code changes to address these issues have been developed and tested within surface-only simulations. These changes sit entirely within the main code of CABLE and do not impact the coupling to the UM. These changes are implemented without the use of a logical switch. The soil latent heat flux is now evaluated/acts consistently to apply one of four cases

i) evaporation from or dew onto surfaces with no snow and soil surface temperature is above freezing,
ii) sublimation from or frost onto surfaces with snow cover (above a small minimum depth),
iii) evaporation of liquid water in the soil if there is no (or less than the minimum depth of) snow cover and the soil is frozen soil,
iv) deposition of frost onto frozen surfaces with no (or less than minimum depth) snow cover.

Additionally, on iii), the latent heat flux is restricted to prevent the liquid component of the soil moisture dropping below the minimum fraction. These code changes encompass Tickets 122, 135, 136 and 137. Further details are given in the documentation attached to Ticket 137. The necessary code has been included the ACCESS development branch of CABLE, that is expected to be used within ACCESS-CM2.

2.2.2 Indicative results

Figure 2.1 gives an illustration of the improvement in moisture conservation that this code set provides based upon the Tumbarumba FLUXNET site. Noting that the y-axis is expressed as a log-scale, the imbalance in moisture using default CABLE at this site is typically a minor 0.4kgm^{-2}y^{-1} (though this is still significant once scaled up to grid cell or catchment scales). Applying the code set improves conservation by approximately a factor of 50 (factor of 10 from case 2 alone). All remaining periods of 'notable' imbalance occur during snow conditions. These results apply across a range of climatic and biotic zones, with greater improvements seen in regions characterised by transitory snow cover.

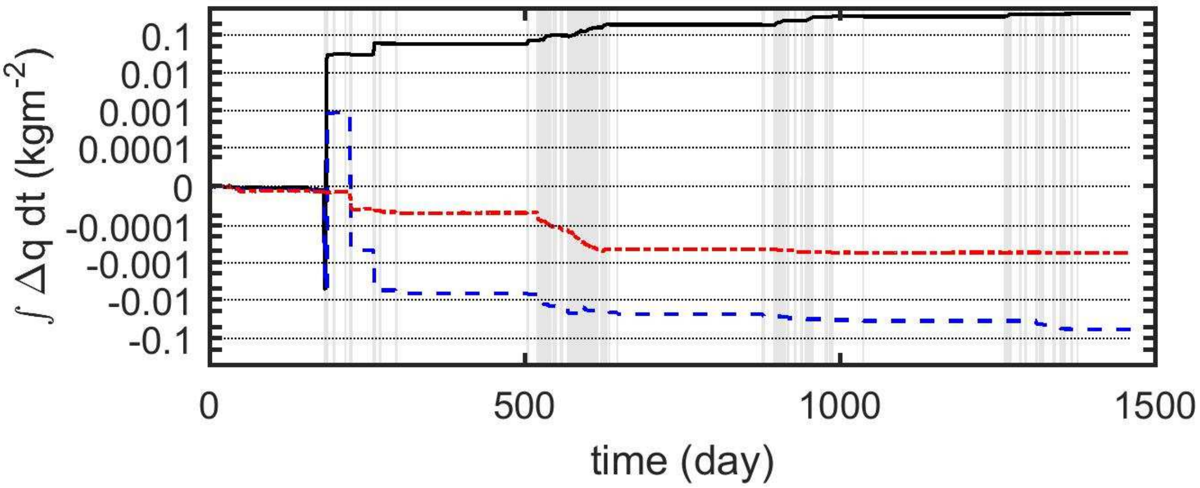

Figure 2.1 Illustration of the improved moisture conservation within a single site, surface-only, CABLE simulation of the Tumbarumba FLUXNET site. Variable shown is the cumulative (from start of simulation) of the water imbalance. The black line show the performance of CABLE 2.2.3, the blue line the performance when case 2 was addressed and the red line when all four cases were addressed. Grey shading indicates times with snow cover. Note the log scale of the y-axis.

Supplementary note: In preparing this report a further potential source of moisture imbalance has been identified within the snow_accum subroutine. A resolution has been identified and documented at Ticket 170. This small adjustment has not been tested nor is it included in the ACCESS development branch (yet).

2.3 The correction terms (Tickets 139 and 164)

As noted earlier, CABLE when operating within ACCESS, uses a different time stepping scheme to from when it is run in surface-only configuration. In particular "correction terms" are applied to the soil energy and water balances so as to provide the fluxes that correspond to the end of the time step. An initial review of these correction terms as in ACCESS1.3 identified several areas of concern, these included

1. that they are incomplete. The turbulent fluxes of sensible and latent heat are corrected, the ground heat and net radiation fluxes are not corrected;
2. the functional form (sensitivity) of the correction terms is incorrect (and overly sensitive);

3. the uncorrected latent heat flux (as per the surface-only model) is restricted by physical limits. The correction terms and, hence, the corrected latent heat flux is not restricted; and that
4. the corrected latent heat flux has an associated implied correction to the soil moisture evolution. In ACCESS1.3 this correction (necessary to conserve water) is applied on the subsequent time step (i.e. conservation is not assured on a time step by time step basis).

At the initial review it was not confirmed whether the completeness issue (1.) was trivial (i.e. at most a diagnostic issue) or critical (i.e. potentially impacting ACCESS performance). Further inspection has revealed that the completeness issue is potentially important in that the net radiation term is used within ACCESS's radiation scheme and hence must be similarly corrected.

Further consideration of the time stepping issue (4.) indicates that this can also directly violate conservation of moisture if the snow cover, direction of potential evaporation or temperature changes markedly across a time step.

Also, at the initial review, it was not appreciated whether the same issues apply to the SLI soil scheme or the more recent Ground Water hydrology scheme and Or option for soil evaporation (as introduced in Ticket 97).

2.3.1 Implementation

A set of code changes to address the issues 1 and 2 have been developed and tested within surface-only simulations. These changes sit within the main code of CABLE (principally cable_canopy) however additional variables are needed and this will impact the technical coupling between CABLE and the UM. The majority of the changes are implemented with the use of a logical switch (L_REV_CORR - as this is a science enhancement), however some elements are applied directly (they are more correctly viewed as bug fixes).

Further background and technical detail is given within the Harman (2016) and the documentation for Tickets 139 and 164 (for the merge with Ticket 97), however it should be noted that

- the correction terms are now definitively not applied when using the SLI soil scheme (but do apply to the soilsnow and ground water hydrology modules) and the code set is structured accordingly;
- the functional forms for the correction terms have been updated and these updates have been expanded to apply to the Ground Water and Or soil evaporation schemes (Ticket 97); and that
- the code set includes additional adjustments to the implementation of the Haverd 'litter' scheme to ensure full consistency.

The necessary code has been included in the ACCESS development branch of CABLE, that is expected to be used within ACCESS-CM2.

2.3.2 Indicative results

The sensitivity terms, from which the correction terms are evaluated (see Harman 2016) documentation, are a critical component of CABLE's soil energy balance whether run as surface-only or within ACCESS. However the correction terms themselves are not activated when CABLE is run in surface-only configuration. To assess the impact of the proposed changes, additional (temporary) code was implemented to apply the correction terms within surface-only simulations and output the "corrected" energy balance. This 'offline-as-ACCESS' capability can only partially test the implementation and does not permit the full set of feedback processes that occur within ACCESS. However this way is a necessary first step towards full testing, especially as ACCESS-CM2 itself is not yet technically stable, and provides initial insights as to whether the changes are acting as expected.

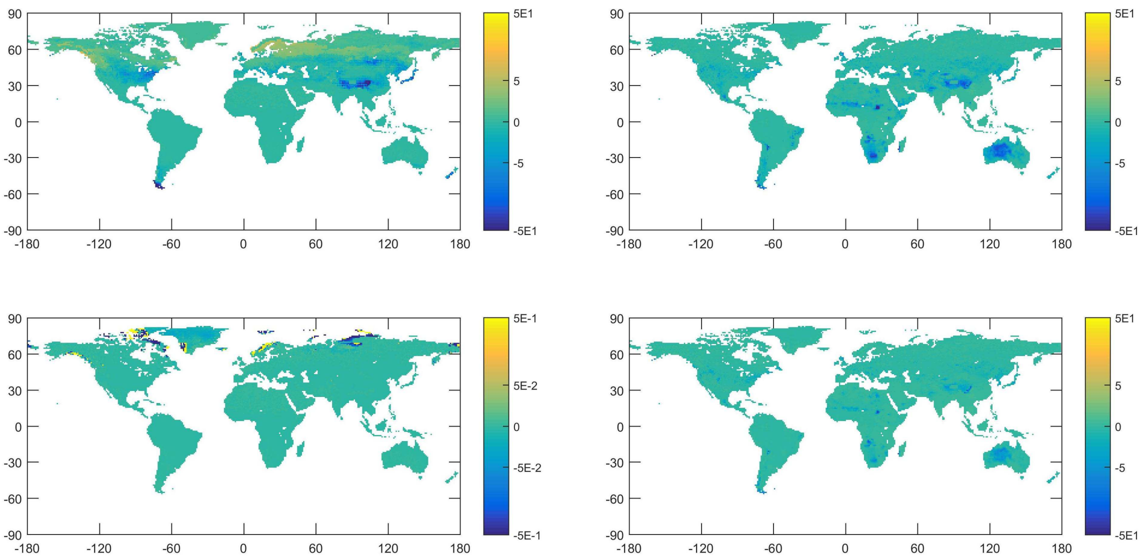

Figure 2.2 Annual accumulated water imbalance (in kg m^{-2}, averaged over 5 years) of a global surface-only (GSWP2) CABLE simulation (using default soilsnow). Top left, CABLE 2.2.3; top right CABLE 2.2.3 with the correction terms applied (i.e. offline-as-ACCESS); bottom left CABLE 2.2.3 with Tickets 137 and 139 applied; bottom right CABLE 2.2.3 with correction terms, Ticket 137 and 139 applied. Note the different colour scales and that the colour scales are nonlinear.

Figure 2.2 shows the 5-year average of the annual accumulated water imbalance for four configurations of CABLE – CABLE surface-only, CABLE surface-only with correction terms and the corresponding two configurations where the code for Ticket 137 and 139 have been applied. It is clear that i) significant improvements (factor 10) have been obtained through the use of the two code sets, ii) the imposition of the correction terms (as per ACCESS) enforces different qualitative patterns of water conservation and that iii) there are still regions where water conservation is an issue in the 'offline-as-ACCESS' configuration.

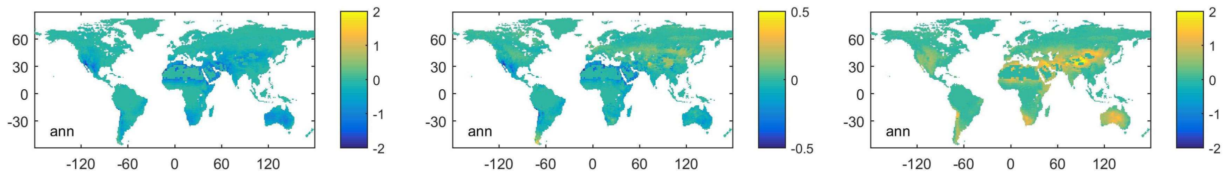

Figure 2.3 Differences in simulated annually averaged near-surface air temperature upon use of the revised correction terms within a global surface-only, GSWP2, simulation. Left: daily minimum screen level temperature; centre, screen level temperature; right, daily maximum screen level temperature. Note the different colour scales.

Figure 2.3 shows the impacts of applying Tickets 137 and 139 have on the annually averaged screen level temperature and daily minimum/maximum temperatures. Note that while the correction terms are only applied when run in coupled mode, the changes to the sensitivity terms apply within all CABLE configurations, including standard surface-only simulations. Impacts are seen primarily in regions with sparse vegetation and in the daily extremes more than the daily average. This reflects the increased control that soil surface temperature has on the near-surface air temperature for those variables. Similar patterns in these differences, if at slightly larger magnitude, are seen when the two Tickets are included in the 'offline-as-ACCESS' configuration (bottom right of Figure 2.2).

2.4 Sequencing and limiting the moisture correction term (Ticket 152)

The third and fourth concerns related to the correction terms noted in Section 2.3 are not addressed by Ticket 139. These are substantially more difficult issues to address and involve:

a) the evaluation of appropriate limits to the correction term to the latent heat flux. CABLE applies limits on the soil evaporation to ensure that the diagnosed transpiration flux can occur without depleting soil moisture below the wilting point (among other factors). This biological limit should be applied to the soil evaporative flux that is used within ACCESS (i.e. the corrected flux);

b) a means to recognise those limits within the soil temperature algorithm; and

c) a means to apply the corrected moisture flux term on the correct time step.

Part c) is further complicated as it requires moving the evaluation of the correction terms, applying the corresponding water increment correctly (accounting for the difference in sequencing between the algorithms for the snow pack and soil moisture) and, importantly, cancelling the existing implementation.

2.4.1 Implementation

A set of code changes to address the issues 3 and 4 have been developed and tested within surface-only simulations. These changes are implemented with the use of a logical switch (L_SSEB). Further background and technical details are provided with the documentation for Ticket 152. The new code sits entirely within CABLE (primarily cable_canopy and cable_soilsnow) however additional variables are needed and this will impact the technical coupling between CABLE and the UM.

To date the code set can only be applied to the default soilsnow scheme – application within the SLI and ground water hydrology schemes has yet to be addressed. Consequently the necessary code has not (yet) been included in the ACCESS development branch of CABLE and, indeed, any implementation will need to be thoroughly reviewed and possibly revised and/or staged to accommodate the other schemes.

2.4.2 Indicative results

Figure 2.4 shows the accumulated water imbalance from corresponding 'offline-as-ACCESS' simulations with the addition of Ticket 152. Ticket 152 only applies within coupled simulations and, correspondingly, makes no impact to the surface-only simulation (left). In contrast water imbalance is improved in the 'offline-as-ACCESS' configuration, in particular the conservation performance in semi-arid regions (where water limitation is more likely) is significantly improved (see Figure 2.2). The remaining regions of concern are common to both configurations and concentrated in locations with permanent ice.

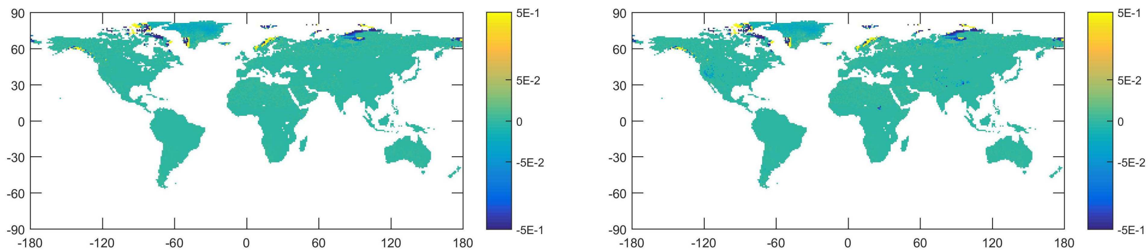

Figure 2.4 Annual accumulated water imbalance (in kg m^{-2}, averaged over 5 years) of a global surface-only (GSWP2) CABLE simulation (using default soilsnow). Left CABLE 2.2.3 with Tickets 137, 139 and 152 applied; right CABLE 2.2.3 with correction terms (offline-as-ACCESS), Ticket 137, 139 and 152 applied. Note that the colour scales are nonlinear.

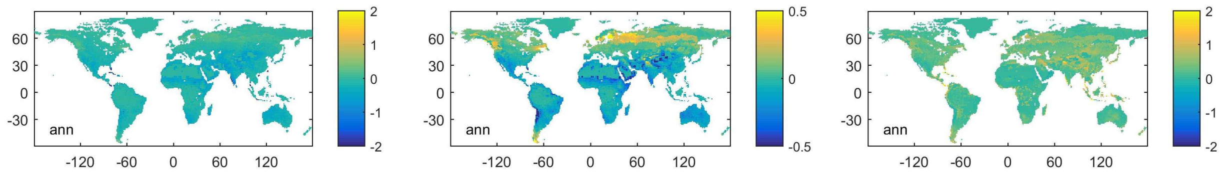

Figure 2.5. Differences in simulated annually averaged near-surface air temperature upon use of the revised sequencing of the soil correction terms, within a global surface-only, GSWP2, CABLE simulation. Left: daily minimum screen level temperature; centre, screen level temperature; right, daily maximum screen level temperature. Note the different colour scales.

Figure 2.5 shows the impacts of applying Tickets 137, 139 and 152 have on the annually averaged screen level temperature and daily minimum/maximum temperatures. Again, while the correction terms are only applied when run in coupled mode, the limits to the sensitivity terms (as used to limit the correction terms) apply within all CABLE configurations, including standard surface-only simulations. As in Figure 2.3 impacts are seen primarily in regions with sparse vegetation and in the daily extremes more than the daily average. However, impacts are also seen now (if only moderate in magnitude), in many other regions of the globe. Similar patterns in these differences, again at slightly larger magnitude, are seen when the three Tickets are included the 'offline-as-ACCESS' case.

3 Other developments to CABLE

Alongside the primary developments to CABLE discussed in Section 2 other science developments, capability enhancements and error fixes have been advanced.

3.1 The friction velocity and consistency of reference heights (Ticket 138)

CABLE permits the use of different reference heights for the forcing wind speed, z_{ua}, and scalars (temperature and humidity), z_{tq}. This is the case when CABLE operates within ACCESS but is not usually the case for single site and surface-only simulations. This capability, however, complicates the calculation of the friction velocity as the equation used must be internally consistent and the two reference heights used correctly. CABLE currently mixes the two reference heights.

The equation (from surface-layer meteorology) used to determine the friction velocity u_* is

$$u_* = U(z)\kappa \Big/ \left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m\left(\frac{z-d}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{L_{MO}}\right)\right] \quad (1)$$

where the *z* used (directly or implicitly) in all locations is the same. ψ_m is a term that quantifies the role of surface heating in setting the turbulent mixing. In practice the current implementation has

$$u_* = U(z_{ua})\kappa \Big/ \left[\ln\left(\frac{z_{ua}}{z_0}\right) - \psi_m\left(\frac{z_{tq}}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{z_{ua}}\frac{z_{tq}}{L_{MO}}\right)\right] \quad (2)$$

where z_{ua} and z_{tq} are assumed to be referenced to the displacement height. The ratio z_{tq}/L_{MO} is the CABLE variable zetar. Ticket 138 restores the intent of the model by calculating

$$u_* = U(z_{ua})\kappa \Big/ \left[\ln\left(\frac{z_{ua}}{z_0}\right) - \psi_m\left(\frac{z_{ua}}{z_{tq}}\frac{z_{tq}}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{z_{tq}}\frac{z_{tq}}{L_{MO}}\right)\right] \quad (3)$$

3.1.1 Implementation

These changes require minor changes to the comp_friction_velocity subroutine within the cable_canopy module of CABLE. A code set has been developed (Ticket 138) and has been included in the ACCESS development branch of CABLE, as expected to be used within ACCESS-CM2.

Additional constraints may be needed so that z_{ua} and z_{tq} are both larger than z_0 and that both are larger than $h_c - d$, i.e. to lie above the canopy. This should form part of the implementation of Ticket 153 at a future date.

3.2 Screen level temperature and humidity (Ticket 154)

Within CABLE the screen level temperature and humidity are purely diagnostic variables – bounded by the values taken at the (prognostic) soil, forcing air and vegetation. However as screen level conditions remain a primary metric for quantifying the performance of LSMs and ESMs such as CABLE and ACCESS respectively, it is important that these diagnostic variables are correctly evaluated.

The evaluation of the screen level variables involves separate numerical algorithms to the rest of CABLE. The basis of the calculations is that

$$\frac{T_{sc} - T_{air}}{T_s - T_{air}} = \frac{r_x(z_0, z_{sc})}{r_x(z_0, z_{ref})} \tag{4}$$

where $r_x(z_1, z_2)$ represents the resistance between heights z_1 & z_2, z_{sc} is the screen level height, z_{ref} is the reference level and z_0 is the roughness length of the soil surface. This is a resistance weighted interpolation between the soil and reference-level temperatures. The functional form of r_x depends on the vegetation characteristics, specifically where z_{sc} sits with respect to *d*. In the case of tall canopies, $z_{sc} \leq d$, the current calculations appear to tie the screen level values closely to the soil temperature, i.e. $r_x(z_0, z_{sc}) \approx r_x(z_0, z_{ref})$. Simple order of magnitude estimates (assuming log-law like turbulence) however that the ratio should take a value between 0.5-0.8.

This mismatch originates from an approximation (and subsequent) error in determining the resistance between the screen level and reference height. For tall canopies the screen level temperature is evaluated from

$$\frac{T_{sc} - T_{air}}{T_s - T_{air}} = \frac{r_x(z_0, z_{sc})}{r_x(z_0, z_{ref})} = \frac{r_x(z_0, z_{sc})}{r_x(z_0, d) + r_x(d, z_{ref})} \tag{5}$$

where $r_x(z_0, d)$ and $r_x(d, z_{ref})$ take values as used to determine CABLE's energy balance and $r_x(z_0, z_{sc})$ is evaluated using the same functional form as $r_x(z_0, d)$. However $r_x(z_0, d)$ is evaluated via an approximation to an integral and the same approximation can be invalid for $r_x(z_0, z_{sc})$.

Analytically (from Kowalczyk et al. 2006, Eq 14 and 17) $r_x(z_0, d)$ is proportional to

$$r_x(z_0, d) \propto \int_{z_0}^{d} \frac{d}{h_c z \exp\{a(z/h - 1)\}}\, \mathrm{d}z \approx \ln\left(\frac{d}{z_0}\right) \frac{\exp\{a\}}{a} \left[1 - \exp\left\{-a\frac{d}{h_c}\right\}\right] \tag{6}$$

(Terms of $\exp\{-a\, z_0/h_c\}$ are neglected and coefficient *a* depends on other canopy parameters)

The current evaluation of $r_x(z_0, z_{sc})$ is

$$r_x(z_0, z_{sc}) \propto \ln\left(\frac{z_{sc}}{z_0}\right) \frac{\exp\{a\}}{a} \left[1 - \exp\left\{-a\frac{z_{sc}}{h_c}\right\}\right] \tag{7}$$

ie. z_{sc} replaces *d* throughout.

However a better approximation is given via

$$r_x(z_0, z_{sc}) \propto \int_{z_0}^{d} \frac{d}{h_c z \exp\{a(z/h - 1)\}}\, \mathrm{d}z - \int_{z_{sc}}^{d} \frac{d}{h_c z \exp\{a(z/h - 1)\}}\, \mathrm{d}z \tag{8}$$

and hence (on replacing z_0 by z_{sc} in the 2nd integral)

$$r_x(z_0, z_{sc}) \propto \ln\left(\frac{d}{z_0}\right) \frac{\exp\{a\}}{a} \left[1 - \exp\left\{-a\frac{d}{h_c}\right\}\right] - \ln\left(\frac{d}{z_{sc}}\right) \frac{\exp\{a\}}{a} \left[\exp\left\{-a\frac{z_{sc}}{h_c}\right\} - \exp\left\{-a\frac{d}{h_c}\right\}\right]$$

i.e.

$$r_x(z_0, z_{sc}) \propto \ln\left(\frac{z_{sc}}{z_0}\right)\frac{\exp\{a\}}{a}\left[1 - \exp\left\{-a\frac{d}{h_c}\right\}\right] + \ln\left(\frac{d}{z_{sc}}\right)\frac{\exp\{a\}}{a}\left[1 - \exp\left\{-a\frac{z_{sc}}{h_c}\right\}\right] \quad (9)$$

The screen level temperature and humidity follow automatically given the change to $r_x(z_0, z_{sc})$.

3.2.1 Implementation

These changes require minor changes to screen level variables calculations within the cable_canopy module of CABLE. A code set has been developed (Ticket 154) and, together with a complementary change (Ticket 67), has been included in the ACCESS development branch of CABLE, as expected to be used within ACCESS-CM2.

Further consideration may be needed to incorporate the role of vegetation state (e.g. leaf area) and the fluxes of sensible and latent heat from the vegetation when determining the screen level variable calculations. Near-surface meteorological conditions (i.e. the vertical profiles of temperature, wind speed and humidity) are determined by the interplay between the surface energy balance and the turbulent transport (at least as modelled within CABLE). This interplay forms the science basis of the within_canopy subroutine of the CABLE. Notably the within_canopy subroutine explicitly depends on both the soil and vegetation fluxes. However the screen level diagnostics, crucial for GCM evaluation, are evaluated independently of the partitioning of the surface fluxes between vegetation and soil.

3.3 Extended output in surface-only CABLE

Somewhat oddly some key variables are not available for output from CABLE 2.2.3, when operated as an LSM. Alongside other updates to CABLE (Ticket 139) is code that permits the output of these variables from CABLE through the surface-only i/o code. The additional diagnostics available are

- screen level temperature and humidity averaged over the reporting period.
- maximum/minimum values of screen level temperature during the reporting period.
- daily maximum/minimum screen level temperature averaged over the reporting period.
- downward flux of momentum averaged over the reporting period.

These output variables are available in single site and global surface-only (i.e. MPI) configurations. The necessary code has been included in the ACCESS development branch of CABLE, as expected to be used within ACCESS-CM2. Updates to the CABLE webpages to alert the community of this capability are needed, and should form part of a general update on the release of the next tagged version of CABLE.

4 The diurnal variation of turbulence as represented by CABLE

The representation of turbulent transfer forms a core component of the biophysics of land surface-atmosphere exchange within CABLE. This representation impacts directly all simulations of the energy balance and surface states, including key metrics such as the screen level air temperature, and indirectly many other aspects of the CABLE. The representation of turbulent transfer is one of the unique features of CABLE, in comparison to other land surface models. Critically turbulence acts to couple the momentum, energy and mass balances at the surface (and indirectly the radiation balance) and is the foremost means of coupling the land to the atmosphere (on short time scales) in climate or Earth system models. The current representation of turbulent transfer in CABLE is built on two underpinning sets of knowledge concerning land-atmosphere exchange – the Localised Near-Field theory (e.g. Raupach 1987) and roughness sublayer theory of canopy turbulence (see Raupach 1994, Raupach et al. 1997), coupled to the Wang and Leuning representation of the coupled canopy energy balance and photosynthesis (Wang and Leuning 1998). Partly because of the multiple fundamentals, several inconsistencies exist in the current representation of turbulence.

4.1 Inconsistencies within default CABLE

Assumptions about the flow and turbulence appear in multiple locations within CABLE, in both the roughness and canopy modules. Specifically

1. The quantification of the displacement height and roughness length (for momentum). This also affects the quantification of the reference heights at which the meteorological forcing is assumed to apply.
2. The quantification of the friction velocity (flux of momentum).
3. The quantification of the wind speed used to determine the leaf boundary-layer resistance to the leaf fluxes of heat, water vapour and carbon dioxide.
4. The specification of the functional forms for the other resistances used to evaluate scalar fluxes.

The underpinning science in these four areas are however not consistent. We have

- 2 sets of assumptions about the depth and form of the roughness sublayer (2 and 4)
- 2 sets of assumptions about the wind speed profile within the canopy (1 and 3)
- Disagreement as to whether diabatic stability plays a role in setting parameters and resistances (all)
- Disagreement as to whether sparse canopies need to formulated differently when setting parameters and resistances (all).

Furthermore some known (i.e. supported by multiple observation sets and well-understood science) dependencies/features of flow within and over canopies are neglected and even contradicted by CABLE. For example the ratio of the friction velocity to wind speed at canopy top has a strong dependency on diabatic stability which is neglected entirely by CABLE (e.g. Harman and Finnigan 2007 and references therein).

The net effect is that (at a minimum, progressively less problematic)

- CABLE assumes that the wind speed profile is discontinuous (and non-smooth) at canopy top. In turn this implies that the momentum flux is discontinuous at canopy top.
- CABLE assumes that the profiles of many turbulent statistics are non-smooth at canopy top.
- CABLE assumes that the turbulence transporting momentum is different to that transporting scalars such as heat and water vapour.
- CABLE assumes that the role of the canopy in setting the turbulence (as quantified by the depth of the roughness sublayer) is different for momentum and scalars.

The combination of these features means that CABLE is internally inconsistent and physically invalid as a model for turbulent exchange. However none of these issues are fatal to CABLE (i.e. lead to a violation of the conservation of momentum, mass or energy either in stand-alone or coupled settings). These issues do impact the performance of CABLE (a 10% error in the resistances is eminently possible from the diabatic stability issues for instance and could lead to a ~1K issue in maximum/minimum temperatures) – and inherently impact any parameter estimation and/or objective assessment of CABLE against independent data. It is highly possible that these issues have led to inappropriate/inaccurate model developments in other parts of CABLE (e.g. through parameter optimisation).

Furthermore, the Haverd et al. 'litter' scheme within CABLE makes further assumptions around the representation of turbulence within a canopy. These changes were originally intended to be internally consistent and connected to the existing formulations. The issues identified above will impact the 'litter' scheme and, through the course of any adjustments to the parent representation, care will be needed to ensure that this scheme remains consistent.

4.2 Roughness length, displacement height and friction velocity

The current formulation of CABLE involves several characteristics that determine the turbulent transfer from the surface to the atmosphere. For momentum these are the roughness length, z_0, and displacement height, d, and, on a time step by time step basis, the friction velocity (equivalently the momentum flux). Given the height of the roughness elements, h_c, and the leaf area index, LAI, these properties are linked by

$$\frac{d}{h_c} = 1 - (1 - \exp\{-x\})/x\,, \quad 2x = c_{CD}\mathrm{LAI}^{\frac{1}{2}} \tag{10}$$

$$\frac{z_0}{h_c} = \left(1 - \frac{d}{h_c}\right)\exp\left[\ln(c_{cw}) - 1 + c_{cw}^{-1} + \frac{\kappa}{\beta}\right] \tag{11}$$

where c_{CD} and c_{cw} are prescribed constants, $\kappa = 0.4$ is von Karman's constant and β is the ratio of the friction velocity, u_*, to wind speed at canopy top, U_h, in neutral conditions. β is given by a prescribed dependence on LAI. These two equations are consistent (derived from) an assumed form for the wind speed profile (in neutral conditions) given by

$$U(z)=\begin{cases}\frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right)+\hat{\psi}\left(\frac{z-d}{z_*-d}\right)\right] & z\geq h_c\\ \frac{u_*}{\beta}\exp\left\{\alpha\left(\frac{z}{h_c}-1\right)\right\} & z\leq h_c\end{cases} \tag{12}$$

where $\hat{\psi}$ quantifies the influence of roughness sublayer turbulence on the profile of wind speed

$$\hat{\psi}(\hat{z})=\begin{cases}\ln(\hat{z}^{-1})+\hat{z}-1 & \hat{z}\leq 1\\ 0 & \hat{z}>1\end{cases},\qquad z_*-d=c_{cw}(h_c-d) \tag{13}$$

and α (CABLE variable rough%coexp) is found by equating the gradient of $U(z)$ at canopy top (equivalently equating momentum fluxes) as

$$\alpha=\frac{\beta}{c_{cw}(1-d/h_c)\kappa} \tag{14}$$

A subtlety: d/h_c is further formulated assuming a within-canopy wind speed profile with $2\alpha=c_{CD}\mathrm{LAI}^{1/2}$ (i.e. the d/h_c and $U(z)$ are themselves inconsistent) – this inconsistency is not addressed here as it would require revisions to the underpinning theory.

A further subtlety: Harman and Finnigan (2007) demonstrate that neither *d* nor z_0 are fixed properties of the surface and instead vary with the flow. To incorporate this variation would require revisions to the underpinning theory and significant changes in implementation.

On time step by time step basis the friction velocity is determined from the forcing wind speed via an assumed wind speed profile of the form

$$u_*=U(z)\kappa\Big/\left[\ln\left(\frac{z-d}{z_0}\right)-\psi_m\left(\frac{z-d}{L_{MO}}\right)+\psi_m\left(\frac{z_0}{L_{MO}}\right)\right]$$

where ψ_m is the standard Monin-Obukhov stability function that quantifies the impact of diabatic stability (i.e. the combination of sensible heat, latent heat and momentum flux) on the wind speed profile. This is consistent with the vertical gradient of the wind speed profile being given by

$$\frac{\mathrm{d}U}{\mathrm{d}z}=\frac{u_*}{\kappa(z-d)}\phi_m\left(\frac{z-d}{L_{MO}}\right)$$

with ϕ_m a similarity function describing the role of stability in setting the wind speed profile (vertical differential of ψ_m).

Immediately there are three issues (see Fig 4.1)

i. The assumed wind speed profiles used to calculate z_0 and u_* are different. The former includes roughness sublayer effects, the latter only diabatic stability (L_{MO}).
ii. β is assumed constant, yet the functional form for u_* implies that it must vary with diabatic stability. The assumed wind speed profile is therefore discontinuous at canopy top, unless the atmosphere is neutrally stratified.
iii. α is assumed constant, yet the functional forms implies that it too must vary with diabatic stability. The gradient of the assumed wind speed profile is also discontinuous at canopy top. α is critical to the quantification of the leaf boundary-layer conductances in the leaf energy balance and photosynthesis calculations.

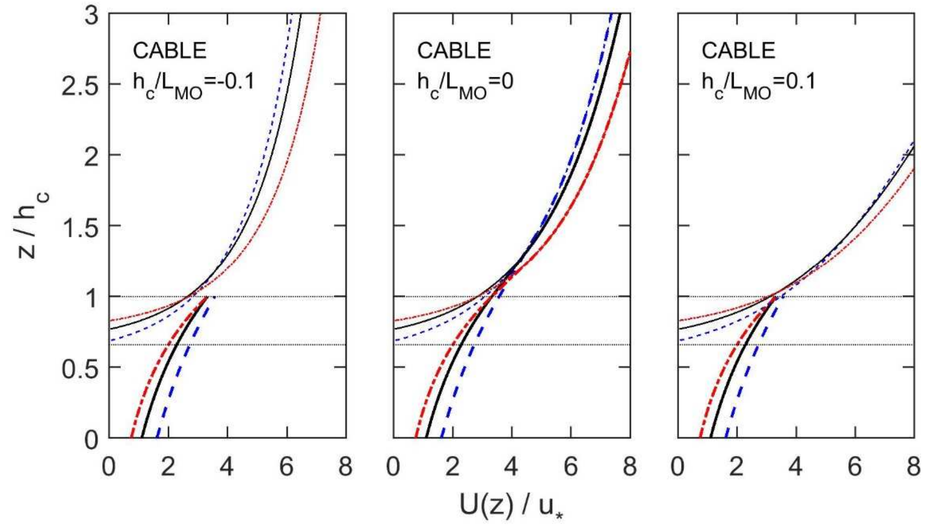

Figure 4.1. Illustration of the assumed wind speed profile, normalised by $\boldsymbol{u_*}$, as used in difference parts of the current CABLE trunk under different diabatic stabilities (as quantified by $\boldsymbol{h_c/L_{MO}}$). The colours show cases for different values of LAI (0.5 blue, 1 black and 2 red). The thick lines show the profiles assumed when determining d and $\boldsymbol{z_0}$ from neutrally stratified conditions (central panel) as used for the forced component of the leaf level conductance (in all stratifications). The thin lines show the profile assumed when evaluating $\boldsymbol{u_*}$ given a reference level wind speed.

4.2.1 Resolution

To address these internal contradictions a set of adjustments need to be made and tested. We will, for now and in contradiction to the RSL research of Harman and Finnigan (2007), assume that d, z_0 and c_{cw} can be held constant at the values taken in neutrally stratified conditions. The calculation of the friction velocity can then proceed from

$$\frac{\mathrm{d}U}{\mathrm{d}z} = \frac{u_*}{\kappa(z-d)}\phi_m\left(\frac{z-d}{L_{MO}}\right)\hat{\phi}\left(\frac{z-d}{z_*-d}\right), \quad \hat{\phi}\left(\frac{z-d}{z_*-d}\right) = \frac{z-d}{z_*-d} \tag{15}$$

This differential equation is problematic to solve, however a reasonable approximation is given by

$$U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right) + \hat{\psi}\left(\frac{z-d}{z_*-d}\right)\phi_m\left(\frac{z_*-d}{L_{MO}}\right) - \psi_m\left(\frac{z-d}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{L_{MO}}\right)\right] \tag{16}$$

which can be used to quantify u_*, given U at a reference height above the canopy.

Corresponding changes are also required to β and α. First

$$\beta = \kappa/\left[\ln\left(\frac{h_c-d}{z_0}\right) + \hat{\psi}\left(\frac{h_c-d}{z_*-d}\right)\phi_m\left(\frac{z_*-d}{L_{MO}}\right) - \psi_m\left(\frac{h_c-d}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{L_{MO}}\right)\right] \tag{17}$$

In neutral conditions (17) gives the same value as that assumed when determining z_0 since then

$$\beta = \kappa/\left[\frac{\kappa}{\beta_N} + \hat{\psi}\left(\frac{h_c-d}{z_*-d}\right)\left[\phi_m\left(\frac{z_*-d}{L_{MO}}\right) - 1\right] - \psi_m\left(\frac{h_c-d}{L_{MO}}\right) + \psi_m\left(\frac{z_0}{L_{MO}}\right)\right] \tag{17'}$$

Second

$$\alpha = \frac{\beta}{\kappa(1-d/h_c)}\hat{\phi}\left(\frac{h_c-d}{z_*-d}\right)\phi_m\left(\frac{h_c-d}{L_{MO}}\right) = \frac{\beta}{\kappa c_{cw}(1-d/h_c)}\phi_m\left(\frac{h_c-d}{L_{MO}}\right) \tag{18}$$

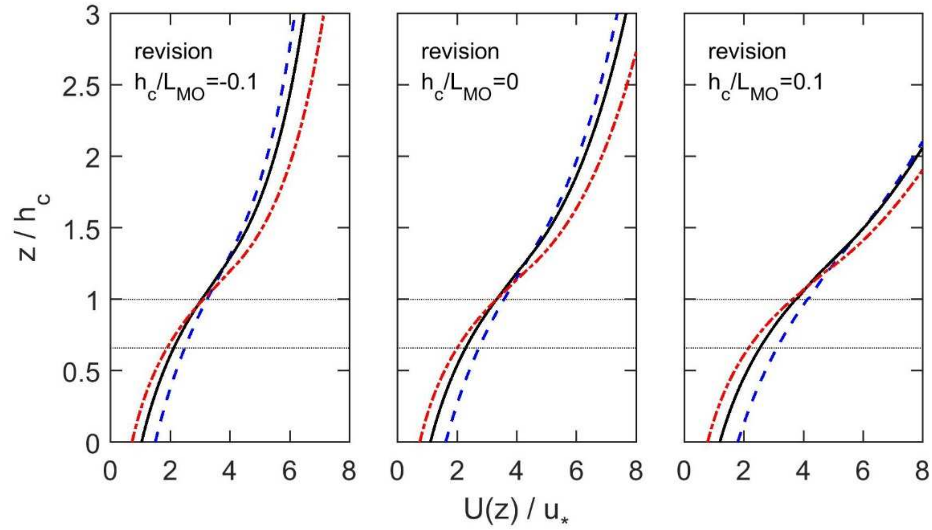

Figure 4.2. Illustration of the wind speed profiles after revision as used in all parts of CABLE. Colours/lines refer as per Fig 4.1.

These modifications would result in a model for the wind speed profile that is continuous and smooth within and above the canopy in all conditions (see Fig 4.2). The wind speed profile that drives the leaf level conductance in the leaf energy balance/photosynthesis calculations would also be consistent (equal).

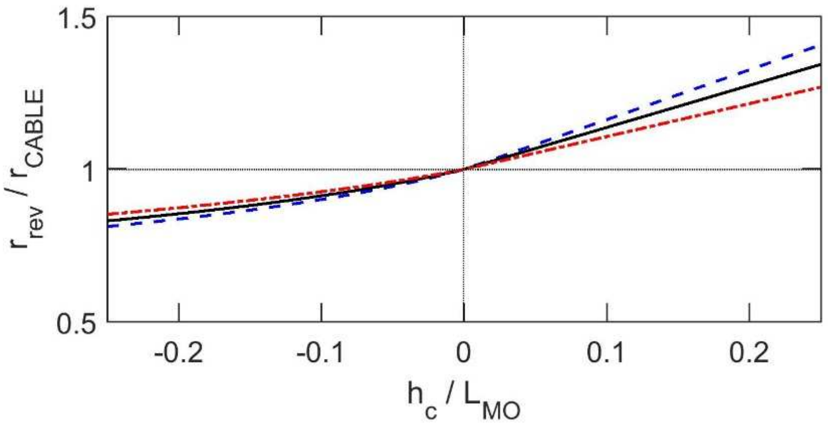

Figure 4.3. Relative change in the leaf level resistance, as driven by changes in both $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$, with changing diabatic stability. Colours refer to the same cases as Fig 4.1 and 4.2.

As noted the change in the assumed wind speed profile implies a change in the forced conductance that appears in the leaf level energy balance (CABLE variable gbhu). Fig 4.3 shows the relative change to the corresponding resistance. In stably stratified conditions ($H < 0$) the resistance increases, decoupling the canopy and soil from the overlying atmosphere; the converse occurs in unstably stratified conditions. The magnitude of the relative change is typically around 20% from the current calculations for commonly occurring conditions ($|h_c/L_{MO}| < 0.1$).

4.2.2 Implementation

These proposed changes require two sets of changes to CABLE.

1. The subroutine that calculates the friction velocity (canopy%us, routine comp_friction_vel) needs to be updated to reflect the updated wind speed profile (16).
2. The roughness module needs to be extended to permit the update to both β (rough%usuh) and α (rough%coexp) as the stability variable (zetar) changes. All other rough% variables that derive from these also need to be recalculated. This update would be calculated inside the stability iteration loop of the define_canopy subroutine. This does represent a modest increase in the computational overhead of roughness component of CABLE.

4.3 Resistance network for scalars

In CABLE the wind speed profile/momentum flux are linked using conventional mixing-length derived surface layer and canopy profiles. In contrast, the scalar profiles and fluxes are linked through a resistance network determined via LNF theory (CABLE documentation, Kowalczyk et al. 2006). Under this theory the vertical flux of scalar, with concentration *x*, is given by

$$F_x = \frac{x(z_1) - x(z_2)}{r_x(z_1, z_2)}, \qquad z_1 < z_2 \tag{19}$$

with the resistance, r_x, given by

$$r_x = \int_{z_1}^{z_2} \frac{1}{K_f(z)} \mathrm{d}z = \int_{z_1}^{z_2} \frac{1}{\sigma_w^2(z) T_L(z)} \mathrm{d}z \tag{20}$$

where K_f is the far-field diffusivity, σ_w^2 the variance of the vertical velocity and T_L the Lagrangian time scale. CABLE specifies profiles of σ_w^2 and T_L that account for canopy turbulence and which revert back towards standard surface layer forms with increasing height above the canopy.

Specifically

$$\sigma_w^2(z) = u_*^2 a_3^2 \min\left[1, \exp\left\{c_{sw} \mathrm{LAI} \left(\frac{z}{h_c} - 1\right)\right\}\right] \tag{21}$$

i.e. a continuous function that decreases exponentially within the canopy and is constant above it[5]. In CABLE $a_3 = 1.25$ and $c_{sw} = 0.5$ are prescribed constants. This is somewhat in contradiction to observations; a_3 is known to vary with stability (takes a minimum in neutral conditions). Furthermore as c_{sw} quantifies the depth scale for the velocity variance within the canopy, the physics of canopy turbulence strongly indicates this should have a corresponding variation to the depth scale of the mean wind speed profile within the canopy, α; c_{sw} should be expected to vary with stability[6].

[5] Note that Eq 12 in the CABLE documentation has a typographic error and is not what is coded/assumed.

[6] The Haverd 'litter' scheme incorporates such a variation.

The Lagrangian time scale is given by

$$T_L(z) = \begin{cases} \dfrac{\kappa(z-d)}{a_3^2 u_* \phi_h([z-d]/L_{MO})} & z \geq z_{ruf} \\ \dfrac{f_{sp} c_{TL} h_c}{u_*} & d \leq z \leq z_{ruf} \\ \dfrac{f_{sp} c_{TL} h_c z}{u_* d} & z \leq d \end{cases} \tag{22}$$

where ϕ_h is a similarity for scalar transfer (corresponding to ϕ_m earlier), $f_{sp}(\mathrm{LAI})$ is a sparseness factor and z_{ruf} is the height of the roughness sublayer for scalars. z_{ruf} is quantified by requiring T_L to be continuous in neutral ($\phi_h = 1$) conditions i.e.

$$z_{ruf} = d + \frac{a_3^2 f_{sp} c_{TL} h_c}{\kappa} \tag{23}$$

and is then assumed constant. Above z_{ruf}, $u_* T_L$ is parameterised to vary with diabatic stability but this product is constant below. In non-neutral conditions this dependence above z_{ruf} leads to $u_* T_L$ being discontinuous at z_{ruf} – this is unphysical (see Fig 4.4 left).

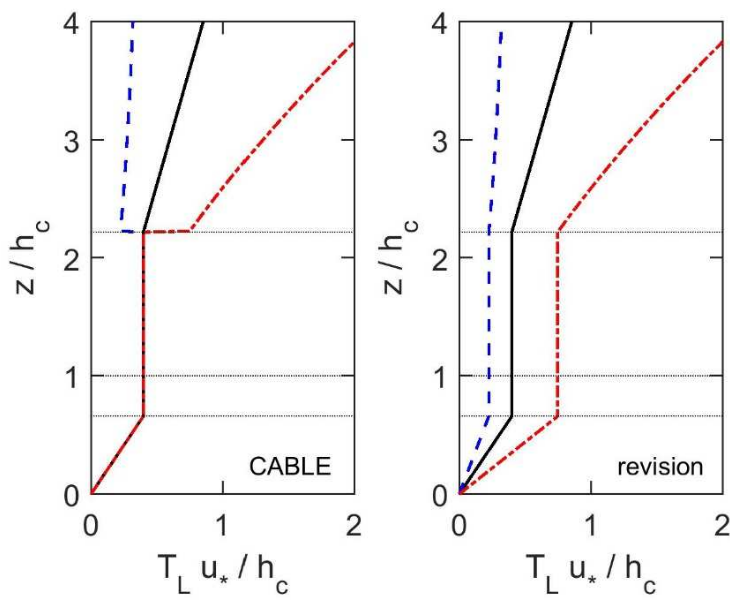

Figure 4.4. Current (left) and proposed (right) profiles for the Lagrangian time scale in neutral (black), unstably stratified (red) and stably stratified (blue) conditions (LAI=1). Note the discontinuity at height z_{ruf} (left)

4.3.1 Resolution

There are (at least) two potential methods to rectify this issue: The simplest retains the functional forms for σ_w^2 and T_L but re-evaluates z_{ruf} to be given by the implicit equation

$$z_{ruf} = d + \frac{a_3^2 f_{sp} c_{TL} h_c \, \phi_h\left(\left[z_{ruf} - d\right]/L_{MO}\right)}{\kappa}$$

This equation requires numerical, iterative solution (especially in diabatically unstable conditions). It also implies that the depth of the scalar roughness sublayer increases with increasing diabatic stability - counter to observations and physical intuition.

A second option (see Fig 4.4 right) is to assume that z_{ruf} is constant and the profile of T_L below z_{ruf} is adjusted to accommodate. Specifically

$$T_L(z) = \begin{cases} \dfrac{\kappa z}{a_3^2 u_* \phi_h([z-d]/L_{MO})} & z \geq z_{ruf} \\ \dfrac{f_{sp} c_{TL} h_c}{u_* \phi_h([z_{ruf}-d]/L_{MO})} \dfrac{a_{3N}^2}{a_3^2} & d \leq z \leq z_{ruf} \\ \dfrac{f_{sp} c_{TL} h_c z}{u_* d \phi_h([z_{ruf}-d]/L_{MO})} \dfrac{a_{3N}^2}{a_3^2} & z \leq d \end{cases} \qquad (24)$$

where (for generality) a_3^2 is allowed to vary from its value in neutrally stratified conditions, a_{3N}^2. In practice – as T_L is multiplied by σ_w^2 in the definition of K_f and hence in r_x – any variation in a_3^2 does not make a quantitative difference to the resistance network.

This adjustment of T_L is reflected in the resistance network as a multiplicative factor of $\phi_h([z_{ruf}-d]/L_{MO})$ being applied to each of the resistances for scalar transfer between the reference level and soil (i.e. rough%rt1usa, rough%rt1usb, rough%rt1usc and rough%rt0us) (see Fig 4.5). Again the resistance to transfer in stably (unstably) stratified conditions is increased (decreased).

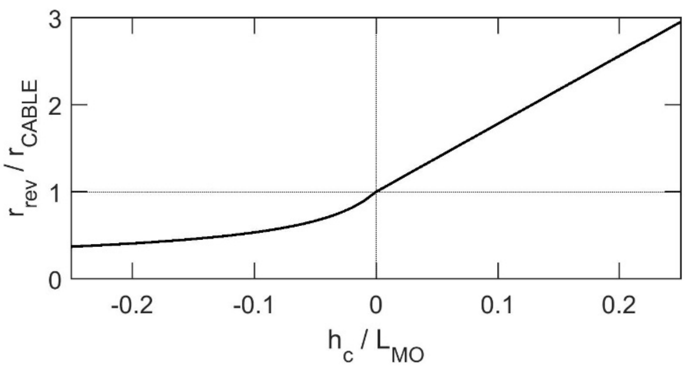

Figure 4.5. Relative change to the soil-z_{ruf} aerodynamic resistance, as driven by changes in T_L, as the diabatic stability varies. The LAI is 1.

These modifications would result in a model that implies continuous profiles of σ_w^2 and T_L through the canopy and which are consistent with observed dependencies in both quantities. Corresponding changes are also required in the calculation of some diagnostic variables that use the resistance network e.g. the screen level variables.

4.3.2 Implementation

These changes require just one set of changes to CABLE:

- The roughness module needs to be extended to permit the update of the resistances and associated temporary variables (rough%term2 – rough%term5) as the stability variable (zetar) changes. This update would be calculated inside the stability iteration loop of the define_canopy subroutine (i.e. alongside the previous update).

However, given the relative uncertainty around the choice of implementation, it is clear that additional research will be needed to carefully test any change to this component of CABLE.

4.4 Depth scale of the vertical velocity variance

As discussed above CABLE assumes a vertical profile of σ_w^2 in the formulation of the aerodynamic resistances for scalar transfer. This profile is assumed invariant to changes in diabatic stability, however canopy turbulence theory would indicate that this is not the case. While the detail of changes will be specific to the site of interest two general effects are likely to occur

i. The ratio of σ_w^2/u_*^2 (at canopy top will vary), and
ii. The vertical variation (or depth scale, c_{sw}) of σ_w^2/u_*^2 will change in a manner commensurate to the changes in the wind speed profile.

Of these changes i) is largely irrelevant as there is direct compensation in the profile of T_L. However the depth scale change is not captured. The 'litter' scheme of Haverd et al. (2013) includes the corresponding change and it is proposed that this be extended to all simulations. Fig 4.6 shows the relative change to the within-canopy aerodynamic resistance that would occur. This illustrates the other proposed changes are of equivalent magnitude (importance) to existing modifications to CABLE's resistance network that have been demonstrated to improve overall model importance.

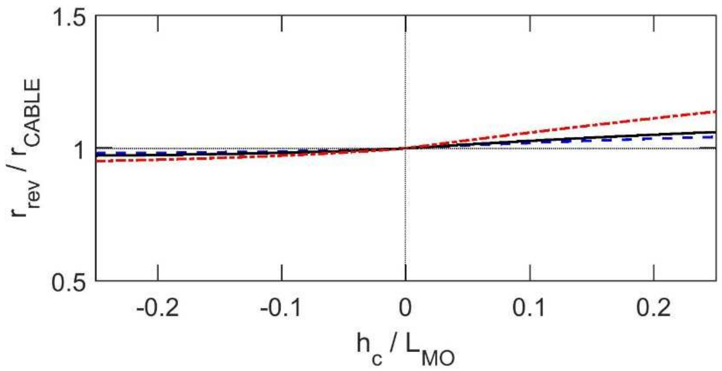

Figure4.6. Relative change to the soil-$\boldsymbol{h_c}$ aerodynamic resistance, as driven by changes in $\boldsymbol{c_{sw}}$ commensurate to changes in $\boldsymbol{\alpha}$, as the diabatic stability varies. The colours show cases for different values of LAI (0.5 blue, 1 black and 2 red)

4.5 Order of magnitude estimates

Any assessment of the net effect of these changes on the simulated surface state and energy balance from CABLE is complicated by two factors. First the relative magnitudes of the aerodynamic and leaf-level resistances are site and meteorology specific and differ when viewed from the soil, sunlit and/or shaded leaves. In general though the leaf level resistance is larger so relatively smaller changes here (Fig 4.3) are likely more important to the net than the larger changes in the aerodynamic terms (Fig 4.5 and 4.6). Second any change in formulation will trigger as set of feedback processes within CABLE. These feedbacks are as important in determining the net impacts on the simulation as the direct effect.

As the primary metrics to validate a land surface model inherently involve either prognostic variables or diagnostics based upon those prognostic variables, it is extremely difficult to ascertain even broad estimates of the impact of a particular model change. In this particular case we are also faced with the challenge that the response of CABLE in surface-only mode may be quite different to that when coupled within ACCESS as the proposed changes tackle one means of coupling (the turbulent fluxes). Consequently these changes will trigger feedback processes within ACCESS but not in surface-only mode.

However, using *some easily-refutable assumptions*, the output of a surface-only simulation from the Tumbarumba Fluxnet site, and a simple approximation to the expected change upon the resistances, gives that we could expect decreases of **up to 2K in the predictions of the diurnal maximum of screen level temperature** (at that site). The decreases are largest when the difference between screen level and reference level air temperature are large (i.e. light winds, strong radiation). In particular this means that the decreases are largest during the summertime and for taller (and sparser) canopies. Somewhat surprisingly the same set of approximations also indicates that **the predicted diurnal minimum of screen level temperature would also decrease by up to 0.5K** at the site (the resistance between the surface and air increases in stably stratified conditions, lowering the surface temperature, which pulls the screen level temperature down with it). A proper estimation of the impact of these changes, even within surface-only simulations, would require actually implementation of the schemes within CABLE.

4.6 Concluding comment

Section 4 has highlighted a number of concerns with the current model for and implementation of turbulent transfer within CABLE. The above discussion indicates that the issues manifest as differences/errors in the variation of the simulated surface transfer as the diabatic stability of the near-surface atmosphere varies, i.e. the diurnal cycle. It is therefore reasonable to expect that i) the simulated extremes in near-surface conditions may be particularly affected by these issues and ii) longer-term (e.g. monthly) averages are less impacted. The CABLE community has recognised that the current code (roughness module) needs attention (Ticket 153). It is suggested that the science highlighted here forms part of the rationale for such a dedicated effort in the future.

5 Other considerations

Looking further ahead neither the UM nor CABLE are fixed, both continue to undergo technical and scientific advancement. The following repeats the overview of prospective and known developments in both CABLE and the UM from Harman (2016) 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.
- A new dynamic core of the UM may have substantive implications for the technical aspects of the coupling (Lfric).
- The potential role for LiS to serve as a means of coupling CABLE to the UM.
- Prognostic phenology and population dynamics, including fire and land cover change (POP).
- 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 and in non-stationary conditions.
- 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 (forms part of Ticket 132).
- The representation of complex landscapes, including urban and inland water.
- Extensions in the UM and CABLE to facilitate multi-layer canopy surfaces.
- The representation of sub-grid scale complexity, including topography, within surface exchange schemes.
- Extensions to facilitate other chemical species.

In addition, discussions within the CABLE community have highlighted several research areas that may require further consideration of the coupling of CABLE within ACCESS:

- the representation of permafrost in Earth system science scenarios.
- the representation of irrigation and water diversions (and fertiliser use) as part of land use assessment.
- an added capability to prescribe land states/land fluxes within ACCESS (e.g. LS3MIP and GLACE-type simulations, Ticket 96).

6 Conclusions and future plans

A review of the scientific and technical coupling of CABLE and the UM within the Earth System Model ACCESS (Harman 2016) highlighted two areas of concern - see Section 2. Substantial progress has since been accomplished in developing, implementing and testing code developments aimed at addressing these concerns. These developments have primarily targeted the scientific basis of coupling between CABLE and the UM, however additional efforts have eventuated concerning conservation of water (Section 2.2) and ensuring consistency between the science basis of the model and the code (Section 3). To date, 13 Tickets documenting these issues and/or updates have been submitted to the CABLE code management system. The majority of these developments have been, or are in the process of being, incorporated in the version of CABLE that is anticipated to be used within ACCESS-CM2, and potentially contributing towards CMIP6 (share/vn10.6_CABLE).

Testing of many of the developments has been delayed by the need to develop and test code for use in multiple configurations of ACCESS and the unfortunate, ongoing, technical issues surrounding the creation of a technically stable (initial) version of ACCESS-CM2. Furthermore, as CABLE is a community model, there have been occasions where multiple development lines have occurred simultaneously that address the same, or connected, parts of the CABLE code. As these developments are finalised and committed particular care is required to merge these development lines, both technically and scientifically. This has been, and will continue to be, the case when reconciling the developments described here with both the SLI soil scheme and the recent advances in the representation of ground water hydrology. A key example of this issue is the still unresolved issue of applying biophysical limits onto the corrected latent heat (in ACCESS) and the application of the correction to the soil evaporation on the correct time step (Harman 2016 and Section 2.4).

The immediate future focus for this project will be strongly contingent on the community's needs and plans for ACCESS-CM2 and participation in CMIP6. At least initially, work should continue on implementing and merging the code updates into a comprehensive and stable version of CABLE for ACCESS. Subsequent activity will require the systematic testing of different configurations of CABLE, across different platforms (surface-only, AMIP, coupled climate and ESM), as needed to inform a decision of the baseline configuration for use in the CMIP6. This will require continued collaboration with the broader CABLE community.

In the medium-longer term there are several options for ongoing work, with the priority to be determined through consultation with some view to the broader community's needs and research interests. These options include

- refining the representation of turbulent exchange within CABLE (Section 4).
- developing additional capability as needed for ACCESS and/or CABLE to participate in other multi-model comparisons (e.g. TILS, LS3MIP, LUMIP, the development of a formal CABLE configuration to replicate ACCESS performance within a surface-only model and the other areas noted in Section 5).

- formal documentation of the configuration of CABLE as used within CMIP6
- scientific assessments and publication of research using the work to date.

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
CMIP6	the sixth iteration of the Coupled Model Intercomparison Project
ESM	Earth System model
JULES	The Joint UK Land Environment Simulator (successor to MOSES)
LSM	Land Surface Model
LS3MIP	the Land Surface Soil and Snow Model Intercomparison project
LUMIP	the Land Use Model Intercomparison Project.
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

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