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CABLE within ACCESS-CM2

Project final report

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Foreword

This report documents the progress of this project and outlines potential areas of 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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Executive summary

The scientific and technical integrity of the coupling of the land surface model, CABLE, to the atmospheric model, the 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 implementation of the coupling within ACCESS1.3 – the version of the model utilised in the fifth Coupled Model Intercomparison Project. While the scientific requirements of the CABLE, ACCESS and UM communities were the primary focus of the review, consideration was also given to technical issues.

This report provides an overview of the CABLE related work undertaken in the development of ACCESS-CM2, the configuration of CABLE as used within the formal submission of ACCESS-CM2 to the sixth Coupled Model Intercomparison Project, a list of supported CABLE options within ACCESS-CM2, and an initial review of the performance of ACCESS-CM2.

The long-term robustness of the ACCESS model relies on safeguarding the coupling, even if not fully scientifically correct, within the UK Met Office's systems. As the code base for the second generation of ACCESS is now finalised, it is appropriate for tasks related to a formal 'merge' of the CABLE and JULES models into one numerical code structure and repository to proceed. The final section of this report outlines the progress towards the merger and lists further tasks that have been identified as necessary following early scoping efforts.

1 Introduction

The CABLE land surface model (LSM) provides a focal point for Australian scientific research around land surface processes within environmental and climate sciences (Kowalczyk et al. 2006, Wang and Leuning 1998). 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 LSM (termed surface only in this report) and as the land component within meteorological, climate system and Earth System models.

The Australian Earth System model ACCESS (Bi et al. 2013, Kowalczyk et al. 2013) 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 (UKMO), from existing models for the different components of the Earth system (Bi et al. 2013). Within ACCESS, CABLE is the preferred representation of the land surface (Kowalczyk et al. 2013), though for some applications the UKMO LSMs, 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). A project to review, and enhance if necessary, the coupling between the CABLE and the atmospheric model's code base (the UM) in ACCESS1.4[1] was initiated (see Harman 2016) as part of the development of the second generation of ACCESS (ACCESS-CM2, Bi et al. 2019). 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[2] 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. Harman (2018) outlined further updates to CABLE, primarily as it interacts with other non-CABLE processes, within ACCESS-CM2. Of note, this effort included modifications to better manage the global water cycle in ACCESS-CM2 via the interface with the iceberg calving and river routing process representation.

In addition to the effort to prepare CABLE for ACCESS-CM2, a second ongoing effort involves a collaborative between CSIRO, CLEX and the UKMO to 'merge' the CABLE and JULES models into one numerical code structure and repository. This is a technical task necessary to secure the successful coupling of CABLE in ACCESS in the long-term and avoid the need for continual technical development in this area. This is particularly pressing given that the UM will shortly be replaced by an atmospheric model (LFric and GungHo) with revised technical interface requirements.

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[1] ACCESS1.4 was a minor update to ACCESS1.3 and forms the physical science component of ACCESS-ESM1.5 (Law et al. 2017)

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

This report documents activities in these two areas, with 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-CM2 and that there are components of CABLE that do not technically function within ACCESS-CM2. Activating and assessing these elements 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 the JULES repository /dev/Share/vn10.6_CABLE/src/ branch.

The current code base(s) for development work within the offline JULES model can be retrieved/inspected at JULES repository /dev/dannyeisenberg/ branch

and the JULES repository /dev/Share/HaC_vn5.4_r14197/src/ branch.

Access to the code requires authorisation to view the UKMO code repository.

2 CABLE within ACCESS-CM2

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 ACCESS co-opts the JULES science and code for the surface-atmosphere exchange over sea and sea-ice, topographic drag and the JULES river runoff scheme, TRIP. In addition, ACCESS-CM2 utilises JULES representations for the surface sources and dry deposition of dust, aerosols (including sea salt) and (when necessary) chemical species but where CABLE derived values for the exchange coefficients are utilised in place of the JULES values.

As a reminder (see Harman 2016, 2017, 2018) the differences between CABLE-within-ACCESS and surface-only 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 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[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.*
- 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 updated 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, in turn, provides a fresh water flux to the ocean at coastal grid cells.

Challenges and their solutions to aspects of the fast components of the coupling between CABLE and the UM were documented in detail by Harman (2017) and Harman (2018). This section provides a very brief overview of developments to the coupling of CABLE in ACCESS-CM2.

[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.

2.1 Developments to CABLE in ACCESS-CM2

Harman (2017) and Harman (2018) outlined several developments to CABLE carried out during the development of ACCESS-CM2. In brief these include

- improvements to the conservation of water internally to CABLE. (Tickets #137 and #170)
- improvements to the 'correction terms' on the implicit call of CABLE within ACCESS, and the facilitation of these improvements in combination with the Or model for soil evaporation and the litter scheme. (#139 and #164)
- refinements to the determination of the friction velocity. (#138)
- refinements to the determination of the screen level temperature and humidity. (#154)
- refinements to the atmospheric forcing used on the implicit calls of CABLE within ACCESS, to be consistent with the expectations of the numerical scheme used by the UM atmospheric boundary layer. (Ticket #132)
- refinements to the collection of state variables that are reset prior to the implicit calls of CABLE within ACCESS.
- refinements to the management of coastal grid cells within ACCESS.
- various improvements to the energy and water conservation of CABLE within ACCESS, including refinement of the surface radiative temperature and ensuring that identical albedos are utilised at all parts of the model on each time step. (Tickets #185, #197, #206)
- rescaling of river outflow to ensure global conservation of water.
- minor modification on permanent ice points to accommodate an iceberg flux in the ocean component of ACCESS.
- the activation of plant functional type dependent root distributions.
- refinements of the roughness and albedo of permanent ice points.

In addition, two sets of refinements have been made within the UM to accommodate CABLE

- the soil moisture variable utilised in the UM's dust source routines has been refined to accommodate CABLE's soil layer depth (Vohralik pers comm.).
- the plant functional type dependent source/sink attributes within the chemistry and aerosol module, UKCA, have been re-ordered[5] to accommodate the differences in type and ordering between JULES and CABLE.

[5] The dry deposition of sea salt aerosol is handled differently from the chemical species by UKCA and assumes details of the JULES configuration which appear inconsistent/incompatible with CABLE. As sea salt aerosol is dominated by maritime processes this element of the intersection between CABLE-JULES-UM-UCKA has therefore been left unedited.

2.2 Configuration of CABLE in ACCESS-CM2

CABLE has multiple science options available, most but not all of which can be utilised within ACCESS. 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 an instance in the code development – as the same configuration should be usable from multiple points/branches over time. The determination of a preferred configuration should involve 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 – or one configuration has additional functionality that is attractive for a particular scientific purpose but worse performance. Unfortunately, the time pressures of CMIP6 have prevented a full assessment of the available options and a decision on configuration primarily resulted from expert opinion and proximity of science to the CMIP5 submission.

CABLE(CM2): The configuration of CABLE within ACCESS-CM2

The configuration of CABLE as used in ACCESS-CM2 - denoted CABLE(CM2) is given below. This is a modest change from the configuration used in ACCESS1.3 and involves no new substantial model components. This operates in partnership with soil and vegetation parameter ancillary files and the code base at the JULES repository /Share/vn10.6_CABLE/src/ branch

l_rev_coupling	TRUE	ACCESS specific coupling changes since ACCESS1.4
l_revcorr	TRUE	
access13roots	FALSE	ACCESS now uses PFT dependent rooting distributions
fwsoil_switch	Haverd2013	a new[6] soil moisture/transpiration model
gs_switch	Medlyn	a new stomatal function model
Or_evap	FALSE	a new soil evaporation model
litter	FALSE	a new litter layer model
soil_thermal_fix	TRUE	a new soil thermal conductivity model

There are also changes (from ACCESS1.4) to a small number of code-based parameter values. The parameters involved are the roughness (increased) and albedos (now differentiated) for permanent ice regions, the leaf-level reflectivity and transmittivity for the vegetated PFTs, the 'convex' parameter in CABLE's photosynthesis model, and the minimum wind speed used to force CABLE is now consistently set at 0.1ms^{-1}. These changes resulted from assessments utilising the GlobAlbedo remote sensing product (Muller et al. 2011), the performance of early, development versions of ACCESS-CM2 and to maintain agreement with revisions in the background literature. Further detail will be given in Harman et al. (2019).

[6] new since ACCESS1.4.

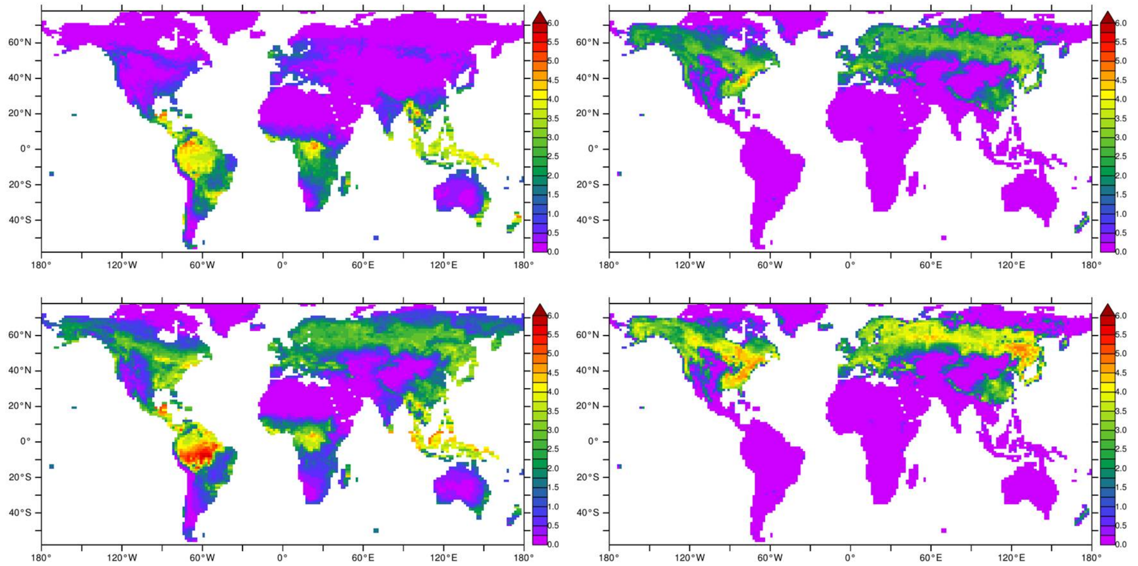

Figure 1: Needleleaf evergreen leaf area index (m^2m^{-2}) in ACCESS1.3 (left) and ACCESS-CM2 (right) in January (upper) and July (lower). As a common leaf area index is used across all PFTs in ACCESS1.3, needleleaf evergreen LAI values are available for locations even where the land cover map indicates no coverage. The ACCESS-CM2 maps combine both land cover and the updated LAI information. Both sets of figures are shown on the ACCESS-CM2 grid. ACCESS1.3 and ACCESS-CM2 differ in their spatial grid, but by half a grid cell only, because of changes in the UM.

ACCESS-CM2 has operated (i.e. run) with all other options for these switches (except for fwsoil_switch where only the ‘standard’ and ‘Haverd2013’ options have been tested). CABLE’s ground water module has undergone recent (re)development (by CLEX) and is implemented in the code base. The code base also includes the SLI soil model (Haverd et al. 2016), hydraulic redistribution module and carbon cycle model CASA-CNP. These four models have yet to be fully tested within ACCESS-CM2 and are not active in the ACCESS-CM2 submission to CMIP6.

ACCESS1.3/1.4 and ACCESS-CM2 utilise land cover maps derived for the NCAR climate models CESM/CCSM and CLM, in combination with a mapping from the CESM PFTs to CABLE’s PFTs. However, in ACCESS1.3, while the land cover is disaggregated across multiple PFTs per grid cell, a single value for the leaf area index (based on the MODIS remote sensing product) was used for all PFTs (Kowalczyk et al. 2013, 2016). From a biological perspective this is highly unlikely to be accurate. NCAR also derive a monthly climatology for the leaf area index for each PFT which is consistent with their land cover maps (Lawrence and Chase 2007, 2010; Lawrence et al. 2012 and references therein). ACCESS-CM2 now applies the same mapping technique to derive a monthly climatology for leaf area index for the CABLE PFTs from the NCAR leaf area index maps. ACCESS-CM2 thus permits different PFTs to have different leaf area index values within a grid cell and different seasonal cycles. Land cover, i.e. the fraction of each grid cell assigned to each PFT, in ACCESS-CM2 is held constant in time, corresponding to potential vegetation cover in 1850 (Lawrence et al. 2010).

A notable consequence, from ACCESS1.3/1.4, is that the Lawrence et al. methodology specifically addresses a known issue associated with the MODIS leaf area product at low solar elevation angles. Evergreen trees are not permitted to lose more than a small (20% for needleleaf trees or 30% for broadleaf trees) proportion of their maximum leaf area over the course of the year. Consequently, the leaf area index of needleleaf trees in the boreal regions is maintained at much higher values through the winter in ACCESS-CM2 when compared to ACCESS1.3 (Figure 1).

2.3 Indicative performance of the land climatology in ACCESS-CM2

A key motivation for the development of ACCESS-CM2 has been participation in CMIP6 and, in particular, completion of the set of DECK[7] simulations (Eyring et al. 2016). As of writing these simulations are still ongoing, however an indicative performance of ACCESS-CM2 can be obtained from simulations completed through the development process[8]. The AMIP simulation considers the response of the atmosphere and land components of the Earth system in response to prescribed (observed) patterns in sea surface temperature (SST) and changes in the composition of the atmosphere. The DECK AMIP focusses on the period 1979-2014 (Eyring et al. 2016), however forcings are provided from 1950 so that the longer-term response to changes in atmospheric composition can be investigated.

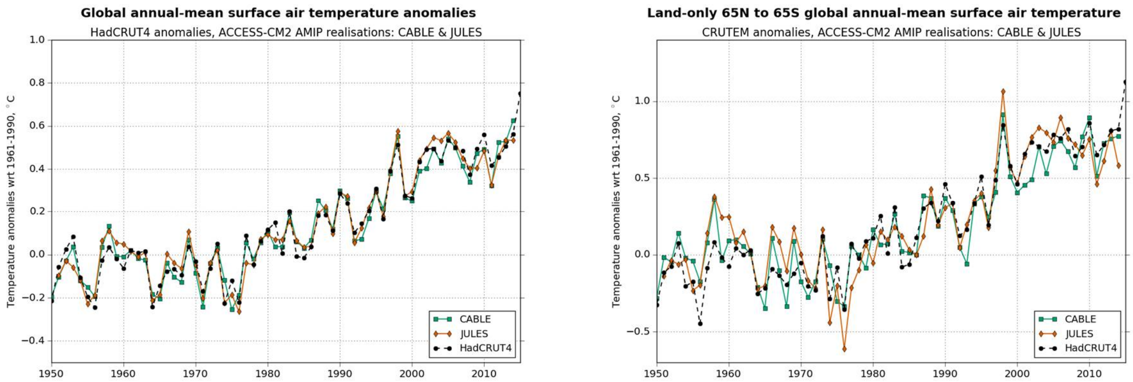

Figure 2: Anomalies in the annually averaged, globally-averaged screen level temperature (left) and annually-averaged screen level air temperature over land (from 65°N-65°S) from AMIP-hist simulation using the full set of CMIP6 forcings. Simulations using both CABLE (bg209[8]) and JULES (suite as896) as the land-surface model are shown. Observations are taken from the HadCRUT4 (left) and CRUTEM4 (right) data sets from the Climate Research Unit (Jones et al. 2010, Osborn and Jones 2014), using a reference period of 1961-1990.

Figure 2 shows the response of the annually-averaged screen level temperature to the CMIP forcings from ACCESS-CM2, for the globe (left) and a sub-domain over the land (right). Included for comparison are the corresponding data when JULES is used in place of CABLE and observation-dominated products from the Climate Research Unit (Jones et al. 2010, Osborn and Jones 2014). Globally (left panel), ACCESS-CM2 can replicate the longer-term trends in screen level air temperature and its interannual variability. However, as the global mean screen level temperature is dominated by the (prescribed) SST such an agreement is to be expected. Any consistent difference in performance between CABLE and JULES cannot be determined in the absence of a more detailed and quantitative analysis.

[7] Participation in CMIP requires the completion of a set of control experiments (Diagnostic, Evaluation and Characterisation of Klima, DECK) and a historical simulation (1850-2014), alongside the voluntary completion of other model intercomparison experiments. The DECK simulations comprise a pre-industrial control, an abrupt 4xCO_2, a 1%/year increasing CO_2 and an AMIP-historical (1979-2014).

[8] ACCESS-CM2 runs were stopped when a CABLE error was found that caused occasional spikes in the 10m wind-speed. The main consequence of this was on the generation of sea-salt aerosol. Suite bg209, shown here, includes this CABLE error. The error has been corrected and the revised pre-industrial control and 4xCO_2 simulations shows little change to the climate or its sensitivity from the earlier simulations.

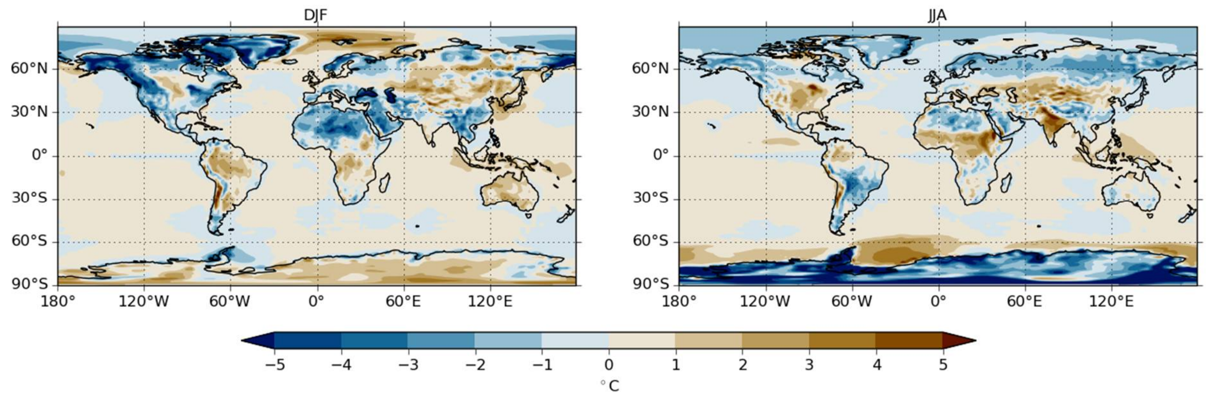

Figure 3: Seasonal biases in mean screen level air temperature from the ACCESS-CM2 AMIP simulation (bg209) using the full set of CMIP6 forcings. Biases are determined relative to the ERA-Interim reanalyses (Berrisford et al. 2011, Dee et al. 2011) for the period 1979-2014.

Focussing on the land regions only (Figure 2 right panel), however, indicates that ACCESS-CM2 can also replicate the longer-term trend and interannual variability away from the control of the oceans. ACCESS-CM2 captures the larger temperature increases in the long-term response over land (0.9-1.0°C between 1950-2010) compared to that in the global mean (0.6-0.7°C). There is an indication that CABLE (and JULES) is overly responsive to the interannual variability in forcing (see 1965-1975 for example), however further analysis is needed to separate the atmospheric response from that due to the land surface model(s).

Global metrics can, of course, hide model weaknesses that occur at smaller time and space scales. Furthermore, model weaknesses often manifest in variables other than the mean screen level temperature. Figures 3-5 show the pattern in seasonally-averaged daily mean, daily maximum and daily minimum screen level temperatures over the period 1979-2014, expressed as biases with respect to the ERA-interim reanalysis (Berrisford et al. 2011, Dee et al. 2011). Figure 3 can be directly compared to Figure 5 of Kowalczyk et al. (2013) that shows the corresponding result from ACCESS1.3 (albeit with differences in forcing). Regional biases of order 2-4°C exist in ACCESS-CM2 and are comparable (if somewhat smaller) to those from ACCESS1.3. Key large-scale regional features in Figure 3 to note are

- The cool bias over the desert regions of northern Africa and western Asia, consistent with ACCESS1.3.
- The warm bias over the intertropical convergence zone, ITCZ, consistent with ACCESS1.3.
- The large warm bias (>3°C) over India in JJA, consistent with ACCESS1.3.
- A cool bias in boreal regions during JJA, in contrast to the neutral/warm bias in ACCESS1.3.
- The warm bias over north America in JJA (3°C) is smaller than that with ACCESS1.3 (6°C) as is the magnitude (and extent) of the warm band across mid-latitude Eurasia.
- The cold bias over north-western North America and the Canadian Archipelago during DJF is a feature in ACCESS-CM2 and not in ACCESS1.3
- Multiple changes in the magnitude and sign of the biases over Antarctica (and near Antarctic waters) between ACCESS-CM2 and ACCESS1.3.

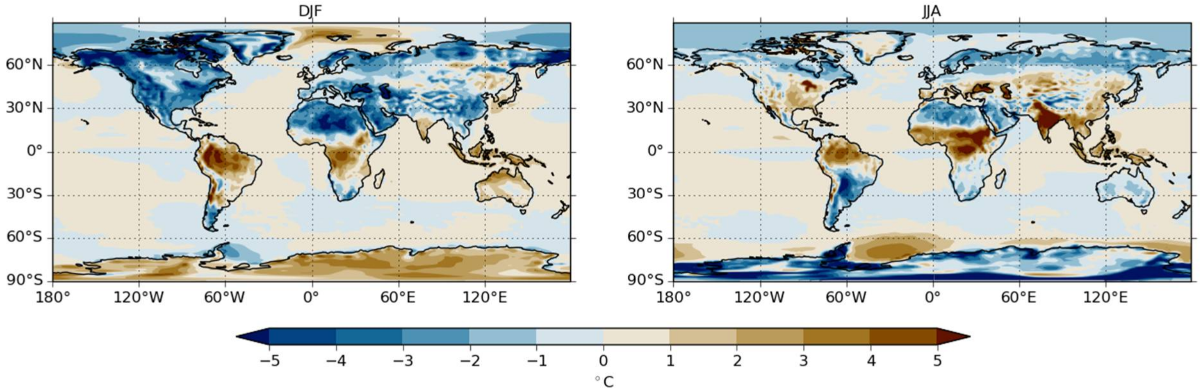

Figure 4. As Figure 3 but for the mean daily maximum screen level air temperature.

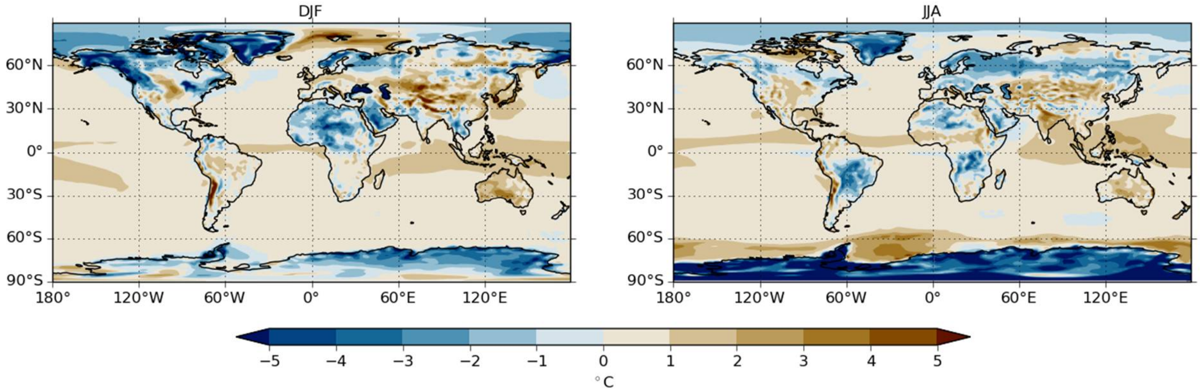

Figure 5. As Figure 3 but for the mean daily minimum screen level air temperature.

The extremes in the screen level temperature are (typically) more sensitive to details in the LSM than the mean climate. Lorenz et al. (2014) (Figures 1 and 2) illustrate that in ACCESS1.3b[9] larger and more systematic biases existed in the mean daily maximum and minimum temperatures than in the mean temperature itself, and that the diurnal temperature range simulated by ACCESS1.3 was typically 3-8°C too small (due to both too cold maximum temperatures and too warm minimum temperatures). Figures 4 and 5 show the corresponding biases in seasonally-averaged daily maximum and minimum temperatures with respect to ERA-interim. As expected, the biases in the diurnal extremes are larger than those for the mean temperature, 3-5°C or greater. Caution should be taken when comparing to the results of Lorenz et al. (2014) as different datasets are used to establish the biases. Figures 4 and 5, indicate that, outside of the intertropical convergence zone, the bias in maximum temperature is generally less than[10] and smaller than that of the bias in minimum temperature. Together this indicates that the seasonal diurnal temperature range in ACCESS-CM2 is smaller in these regions than that in ERA-interim (consistent with ACCESS1.3b, Lorenz et al. 2014). In contrast, within the ITCZ, ACCESS-CM2 biases in maximum temperature are greater than and larger than that for the minimum temperature, with consequent impacts on the simulated diurnal temperature range. This ITCZ feature would appear to be a new feature of ACCESS-CM2, from ACCESS1.3b (Figure 6, Lorenz et al. 2014), however differences in data coverage/type should be assessed before this is confirmed.

[9] ACCESS1.3b utilised the same atmospheric model and configuration as ACCESS1.3 but a different version of CABLE. The version of CABLE differed solely in terms of bug fixes and optical properties (Lorenz et al. 2014).

[10] For clarity: 'less than' means $a < b$ whereas 'smaller than' means $|a| < |b|$.

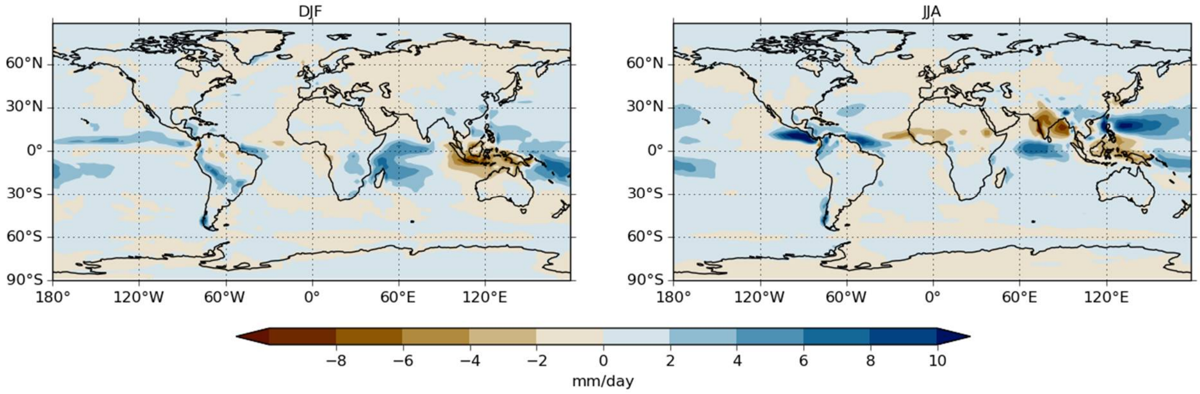

Figure 6: Seasonal biases in precipitation from the ACCESS-CM2 simulation (bg209) using full CMIP6 forcings. Biases are determined relative to the GPCP precipitation dataset (Adler et al. 2003, 2018) over the period 1979-2014 and expressed in mm day^{-1}.

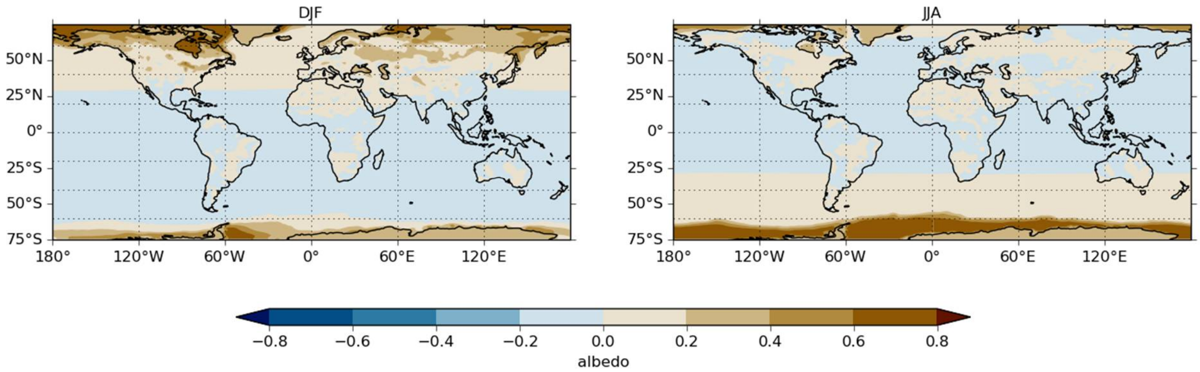

Figure 7: Seasonal biases in land surface albedo from the ACCESS-CM2 simulation (bg209) using full CMIP6 forcings. Biases are determined relative to ERA-interim reanalyses with the albedo determined as $S^{\uparrow}/S^{\downarrow}$ from the averaged total clear sky downwelling $S^{\downarrow}$ and upwelling $S^{\uparrow}$ shortwave radiative fluxes

Lorenz et al. (2014) also noted that the key exception to the trait of ACCESS1.3b underestimating the maximum temperature occurred over North America in JJA. In this region biases in the maximum temperature of +5°C or more accompanied biases in the mean temperature of only (approximately) +3°C. These traits were diagnosed to be linked to both cloud cover and precipitation biases. Within ACCESS-CM2, in contrast, there is little difference in the magnitude and extent of the biases in the JJA mean and maximum daily temperatures in this region (2-3°C).

Biases in temperature are commonly associated with biases in other meteorological variables via the underpinning process representation. Figure 6 shows the corresponding bias in seasonal precipitation. Biases over east Asia (wet), Sahel and India (dry) are consistent with the (cool and warm respectively) near-surface temperature biases (Figures 3) that would be expected due to the corresponding biases in cloud cover and surface evapotranspiration (not shown)[11]. However, other precipitation biases do not have corresponding temperature biases and vice-versa (for example the cool bias over the Sahara) suggesting that other process/properties are also involved.

[11] Note that in AMIP simulations biases in precipitation, cloud cover and/or evaporation are unlikely to be associated with screen-level temperature biases in oceanic regions because of the prescription of the SSTs.

Figure 6 can be contrasted with Figure 3 of Lorenz et al. (2014) and, with care, Figure 9 of Kowalczyk et al. (2013). Other than the wet/dry dipole over east Asia/India, the wet biases over south-eastern Africa and central South America (DJF), and the small magnitude but wide extent of dry (winter) and wet (summer) biases in boreal Eurasia, there are few similarities between the precipitation biases in ACCESS-CM2 and ACCESS1.3(b). The notable dry bias over the maritime continent is a new feature in ACCESS-CM2 and contrasts to wet biases, relative to both the GPCP data and ERA-interim, with ACCESS1.3. Given the multiple changes in process representation in the atmospheric model, such differences in performance are to be expected.

Finally, Figure 7 compares the mean land albedo from ACCESS-CM2 and that of the ERA-interim re-analyses. The albedo is a (the) underpinning constraint on the amount and partitioning of energy at the surface and hence the simulated near-surface climate. Figure 7 shows that the albedo in ACCESS-CM2 is consistently greater than that of ERA-interim over the desert regions of Africa and west Asia. While the difference is modest (less than 0.2) this is enough to explain the cold bias of ACCESS-CM2 relative to the ERA-interim (Figures 3 and 4). Other regional patterns in temperature have no clear relationship to the albedo indicating that atmospheric processes, for example cloud cover and cloud radiative properties, (or other land processes) are more likely causes for these performance issues (e.g. across the ITCZ). The relatively higher values of albedo in the northern hemisphere winter in ACCESS-CM2 compared to ERA-interim, likely reflect differences in the extent and timing of snow cover. However, given the incoming insolation is small during this season, this bias is unlikely to contribute to the biases in climate.

Assessments of the performance of ACCESS-CM2 that explore these issues in more quantitative detail are in preparation (Bodman et al. 2019, Harman et al. 2019 *in prep*).

2.4 Known or suspected issues

As with any large modelling enterprise a series of compromises has had to be made regarding priorities involved in the development of, and of coupling of CABLE within ACCESS-CM2. Primarily for documentation purposes, it is important to note those issues that were identified but not addressed or resolved:

- CABLE (like most LSMs) uses an iteration scheme to solve the coupled momentum and energy balance at the surface. Recent results indicate that CABLE's scheme does not converge in some meteorological conditions. This issue should be explored further.
- The use of, and evaluation of the JULES coupling coefficients (rhokm, rhokh etc.) from CABLE variables should be reviewed. These coefficients are utilised in multiple locations within JULES and ACCESS, most notably in the aerosol code. They often reflect the specific structure of JULES and so may not transfer directly to CABLE.
- ACCESS-CM2 permits the use of the JULES representation of snow transport from canopies (the can_model and can_snow_models) even though CABLE does not permit the accumulation of snow onto the canopy. The UM/JULES configuration of ACCESS-CM2 indicates that this module is active for one PFT type (needleleaf evergreen trees).
- ACCESS-CM2 utilises the JULES formulation and code for the evaluation of the 10m winds. This is potentially inconsistent with CABLE's representation of the wind profile. This issue

has manifested as too high magnitude aerosol source strengths in a development version of ACCESS-CM2, and likely involves the convergence issue noted above.

- ACCESS-CM2 uses elements of the JULES formulation and code for the evaluation of screen level temperature in radiatively decoupled conditions. This is potentially inconsistent with the science in CABLE.
- ACCESS-CM2 uses JULES values for the surface roughness in the evaluation of the topographic drag. This is a consequence of the sequencing of calculations in the explicit call to CABLE.
- On coastal grid cells: ACCESS-CM2 uses the explicit call land fluxes to update the sea and sea-ice energy balance. This contrasts with JULES which uses the implicit call values for the land fluxes in this calculation. Consequently ACCESS-CM2 is not utilising the JULES science as per the original intent.
- CABLE is not providing a value for JULES variables gc and gs during the explicit call. These variables are populated with default values and may be utilised elsewhere within the UM prior to being set in the implicit call.
- CABLE is not reporting the updated potential evaporation variable on the implicit call. The actual evaporation and potential evaporation reported are therefore inconsistent.
- CABLE's general coding standard and documentation, for example the use of hard-wired indices.

More generally, ACCESS-CM2 has retained JULES science options in its code base by default, without the necessary effort/review to ensure that the science basis of those options is compatible with CABLE science. This includes (non-active) methane and nitrogen cycle science.

Additionally, a set of issues have been identified within the core of CABLE's science code during the development of ACCESS-CM2. Further details are provided on the CABLE ticket system:

- For consistency across CABLE's state variables, the time stepping of CABLE canopy water content should be moved out of the cable_canopy routine (Ticket #175).
- The initialization of CABLE's soil moisture in permanent ice regions is inconsistent through the code and between surface-only and coupled configurations (#106, #174)
- CABLE facilitates variation in the soil emissivity, however energy conservation is not obtained if the emissivity does not take a value of 1 (#203).
- Varying the value of the soil roughness length independently of other canopy parameters can cause CABLE to crash for numerical reasons (#205).
- CABLE's sensible heat flux is forced by differences in temperature, whereas the physics requires this to be differences in potential temperature (#206).
- CABLE's lake tile ensures permanent saturation, yet the lake albedo does not (#207, only relevant if the soil colour albedo parameterisation is active).

Finally, there is some confusion concerning the wetland tile in CABLE. In some discussions of CABLE and ACCESS (e.g. Law et al. 2017) the wetland tile is described as permanently saturated (C3 grass); in ACCESS-CM2, and the code base more generally, saturation is not enforced.

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, to couple properly to the UM and be merged within the JULES repository, special technical and structural conditions must be met that CABLE does not automatically satisfy (see Harman 2018 for a longer discussion).

It is almost inevitable that a full agreement between CABLE and JULES cannot be achieved without a fundamental rewrite and extension of CABLE. Consequently, as no alternate approach is currently available, the intent is to retain the current 'iterative' and 'blended' approach into the future and manage conflicts as they emerge. However, this blending of code and co-opting of JULES science and algorithms has led to a complex mix of CABLE and JULES science that resides in a shared layer. This shared layer sits in between the surf_couple interfaces (that couple the UM to JULES) and CABLE's core science 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 a primary challenge for the establishment of JAC.

Following initial efforts and discussions with UKMO researchers two other challenges have emerged for the development of JAC

1. the management of CABLE input and output through the JULES' structures and the rose system.
2. the evolution of the UM-JULES technical coupling in response to the development of LFric.

The development path (agreed with the UKMO) is to first develop the capability to run CABLE through the JULES infrastructure for a single site, in a surface-only configuration. This will require that most CABLE input needs are addressed and will tackle the shared layer of code. In contrast to the current approach in ACCESS-CM2 (which is inclusive by default), in the first instance the updated shared layer in JAC will comprise only that science needed to operate CABLE as a surface only model, i.e. independent of the UM, and will only ever include those parts of JULES that both communities are confident is appropriate. Subsequent developments would activate the capability for global, surface-only simulations and then the capability to function within the UM (or another supported atmospheric model). JULES Ticket #834[12] has been opened to collate

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

discussions on the proposed structure and JULES Ticket #919 documents proposed structural changes to JULES that aim to facilitate the development of JAC.

Progress on the development of JAC has, to date, been slow due to the ongoing requirements of preparing ACCESS-CM2 for CMIP6 and the review process inherent in updating the UKMO models. Two substantive elements of the task have been achieved: First, approximately half of the input requirements can now be read in through the JULES infrastructure and associated rose system. Second, CABLE has been successfully ported into the latest version of JULES in a development form at the JULES repository /dev/Share/HaC_vn5.4_r14197/src/ branch. These two components, however, have not yet been successfully linked so that the HaC branch utilises the ACCESS-CM2 style input structures. Importantly this effort has also successfully addressed one of the outstanding interface concerns namely that, unlike in ACCESS1.3/1.4 and ACCESS-CM2, CABLE's albedos can now be evaluated and utilised on the first-time step of any simulation. This represents a substantial step forward to satisfying the restart reproducibility requirement of JULES (JAC).

4 Conclusions and future developments

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 – for example concerning ice berg calving and the many changes needed due to the advance to ENDGAME dynamics by the UM since ACCESS1.3. Furthermore, some errors within CABLE, which only manifest in a coupled modelling environment, have been identified and resolved (see Harman 2016, 2017). 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 (see Section 2.3). Selective model results have been included here as an illustration only and will be the subject of more comprehensive studies in the future.

The immediate future focus for this project will be directed by participation in CMIP6, including the documentation and analysis of the configuration, CABLE(CM2), and the aim to safeguard the effort to date by formally merging the CABLE (including coupling) and JULES code bases. This will require continued collaboration with and across the broader CABLE community.

In the longer term there are at least three 'capability development' activities needed for CABLE and CABLE-within-ACCESS specifically. First is the activation and testing of those existing CABLE science components within ACCESS. Examples include the ground water and sub-grid scale soil processes models (Decker et al. 2015), the soil-litter-isotope soil model (Haverd et al. 2016) and the Earth system component models (e.g. CASA-CNP, Wang et al. 2010). A potential next step would be that a cross-community exercise rank these existing science components in order of priority for activation within CM2 given the priorities of the CSC, CLEX and other stakeholders. This activity should also identify those stakeholders, researchers and skills that would be needed in the development process(es) to ensure scientific rigour and community engagement.

Second is to facilitate the extension of CABLE to include other terrestrial processes and land cover types. Obvious examples include dedicated representations for the surface exchange over urban areas and inland water bodies, for the impacts of landscape heterogeneity and subgrid scale topography, and the inclusion of processes such as irrigation or saltation/sedimentation for terrestrial sources of aerosols and dust. Some detailed consideration is required to determine the approach taken when developing new capability. The conventional approach is to develop new process representations within the existing code base – this is likely appropriate in some circumstances (e.g. irrigation) particularly for cases where there is interaction with the existing science. However, an alternate approach would be to add more flexibility in the structure of CABLE and/or the interface between CABLE and the UM that permits other specialist models to be utilised side by side with the CABLE core model (in their native code). This second option would facilitate the inclusion of, e.g., the UCLEM urban model (Lipson et al. 2018) and/or one of the many available lake models, without additional extensive effort in recode. It would require some restructuring of CABLE and, particularly, the UM-CABLE interface and input components of ACCESS. The same cross-community exercise, as above, should be used to identify those extensions of CABLE capability that are priorities for the various stakeholders, and to the route for development and inclusion into the CABLE trunk. Importantly this should also identify any needed revisions to the working practices for CABLE developers and the partitioning of responsibilities between researchers and technical support (see below). A clear picture of the technical requirements of JAC and the in-development benchmarking system for CABLE will greatly assist the actual process of extending CABLE.

The third extension would be to facilitate the use of ACCESS derived outputs (and other ESGF/CMIP outputs) as forcing for stand-alone (surface only) CABLE simulations. This capability would be highly beneficial for the efficient spin up of CABLE's slower components (the carbon, nitrogen and phosphorous cycles and any activated dynamic vegetation models) in ACCESS and to perform sensitivity tests. The primary tasks would be the development of input code tailored to the (given) format of the ESGF output, including any necessary interpolation in time, and the ability to read stand-alone restart files within ACCESS-CM2. However, full consistency in the model configuration between the coupled and surface-only models would also be needed. involving all ancillary/parameter information (land cover, soil parameters etc.) and the information included within the restart. This development could be achieved independently of JAC if needed.

Much of the effort in developing CABLE-in-ACCESS and JAC has naturally focussed on the detail of the implementation, incrementing upon the existing code base. An element that is missing, however, is creation of (and agreement on) an overarching 'structure' for CABLE/JAC that a) recognises the inherent differences between CABLE and JULES, b) is of sufficient detail to guide and facilitate the transition of new and existing science from developers into ACCESS (acknowledging the requirements of LFric) and c) aligns with, and is enforced by, the working practices of the CABLE community. Documentation of CABLE is becoming urgent; the latest comprehensive technical documentation of CABLE is now approaching 14 years old (Kowalczyk et al. 2006). The creation of a library of updatable technical documents (i.e. not journal articles) for each of the major components of CABLE that resides and is managed alongside the code repository would be of great value to the community. JAC provides an opportunity and rationale for the development of these and other 'community resources' (including the in-development benchmarking system) but does ultimately rely on resourcing. The stakeholders for CABLE should not underestimate the time and resources needed to develop JAC and these 'community resources', the need for community 'buy-in', or the need to have the appropriate individuals (and skills) involved in constructive ways and suitably empowered. Ultimately the long-term success of JAC (and ACCESS) could depend on these higher-level aspects – rather than getting the technical minutiae correct – and hence should be priorities for the community to address.

Abbreviations and acronyms

ACCESS	Australian Community Climate and Earth System Simulator
ACCESS 1.3	ACCESS (with CABLE) as used within the CMIP5 Project
ACCESS 1.4	a modest update to ACCESS 1.3
ACCESS-ESM	ACCESS variant with the 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 phase of the Coupled Model Intercomparison Project
CMIP6	the sixth phase of the Coupled Model Intercomparison Project
CLEX	the Australian Research Council Centre of Excellence on Climate Extremes
DECK	the core Diagnostic, Evaluation and Characterisation of Klima experiments of CMIP.
ESGF	Earth System Grid Federation
ESM	Earth System model
GungHo	the next generation dynamical core for the UKMO atmospheric 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 computational architecture for the UK Met Office models.
LSM	Land Surface Model
MOSES	The UK Met Office's Surface Exchange Scheme model
PFT	Plant functional type
rose	the configuration and scheduling software for JULES and ACCESS-CM2
TRIFFID	The UK terrestrial carbon cycle and dynamic vegetation model.
UKMO	The UK Met Office
UM	The UK Met Office's atmospheric model, the Unified Model
UNSW	Climate Change Science Centre, University of New South Wales

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