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The Community Atmosphere Biosphere Land Exchange (CABLE) model Roadmap for 2012-2017

Law, R.M., Raupach, M.R., Abramowitz, G., Dharssi, I., Haverd, V., Pitman, A.J., Renzullo, L., Van Dijk, A. and Wang, Y-P

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FOREWORD

The process of writing a roadmap for the CABLE land surface model for 2012-2017 was initiated at the request of the CAWCR Supervisory Committee. A writing team was appointed by the CAWCR director and met in person three times over six months, with numerous other interactions. The Roadmap was presented to the CAWCR Supervisory Committee in June 2012. Discussions on CABLE research priorities from a CABLE community workshop in November 2011 provided helpful background material for the writing team, as did ongoing discussions within the CABLE community on CABLE management options.

The writing team would like to acknowledge the generous and constructive feedback from those who read draft versions of the Roadmap. They also appreciate the valuable help provided by Natalie Barnett in supporting the document preparation.

This Roadmap is published as a CAWCR technical report to facilitate discussion within the CABLE community and the wider land surface community within Australia. We hope that it can be a useful resource document for those working on CABLE development, and for those who apply CABLE to a wide range of research tasks.

We are pleased that the Roadmap reinforces the importance of CABLE as a community model, and that the National Computing Infrastructure provides an appropriate platform for cooperative CABLE development.

Rachel Law and Mike Raupach, on behalf of the roadmap writing team
August 2012

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SUMMARY AND RECOMMENDATIONS

The Community Atmosphere Biosphere Land Exchange (CABLE) model describes land-atmosphere exchanges of energy, carbon, water and momentum, together with related biogeochemical, vegetation-dynamic and disturbance processes. CABLE is coupled with several climate models including the UKMO Unified Model as part of ACCESS1.3, used in CAWCR for IPCC AR5 climate projections. CABLE is also a key part of the Australian contributions to two international projects: RECCAP (REgional Carbon Cycle Assessments and Processes), and LUCID (Land Use Change, IDentification of robust impacts).

Because the land surface is a crossroads in the Earth System, there are multiple societal and policy drivers for land surface modelling. We identify six such drivers, together with their institutional stakeholders and key relationships from a CABLE perspective:

(1) *Weather forecasting:* The policy driver is the need for more accurate weather forecasting services. Value propositions for CABLE are the provision of better land-surface initial conditions, soil moisture, land-atmosphere sensible and latent heat fluxes, and the land-surface radiation balance. The major institutional stakeholder is BoM, and the key route for delivery of CABLE science is through CAWCR.

(2) *Climate change projections:* The policy driver is the need for climate change projections. Value propositions for CABLE are improvements to descriptions of terrestrial energy, water and carbon balances, CO_2 and nutrient feedbacks on water and carbon exchanges, land use change, land surface effects on non-CO_2 greenhouse gases, and changes in terrestrial albedo. The major Australian stakeholder is the Australian community, through Commonwealth and State Governments.

(3) *Water resources management:* The major policy driver is the need for water information, including accurate national water accounts and water resource assessments. This is supported in CSIRO by the Australian Water Resources Assessment (AWRA) modelling suite. The value proposition is to ensure consistency of AWRA and CABLE (as the land surface component of NWP and climate models). Key stakeholders are Commonwealth and State Governments, through COAG.

(4) *Carbon management and accounting:* The policy need is for verification of compliance with international agreements on greenhouse gas mitigation, and development of frameworks for full carbon or greenhouse gas accounting. Working with the National Carbon Accounting System (NCAS) as a key stakeholder, the value proposition for CABLE is to assist in determining the likely effects of climate change on full carbon accounts.

(5) *Environmental information and accounting:* The policy driver is the need for environmental information systems to support comprehensive or "triple-bottom-line" (economic, environmental, social) perspectives on societal goals. The value proposition for CABLE is application of a terrestrial mass and energy balance framework to this endeavour. The key stakeholder is the new Environmental Accounting Branch in the Climate and Water Division of BoM.

(6) *Integrated assessment:* The policy driver is the need for global or regional future scenarios that account for interactions between biophysical processes, resource availabilities, economic development, technological changes and geopolitical shifts. The value proposition for CABLE is better incorporation of interactions between land-surface biophysical processes and climate, productive land use, and ecosystem services. A key stakeholder is the Integrated Carbon Pathways (ICP) program in CSIRO.

The identified external drivers lead to six research areas for CABLE science and development, each with an identified broad research goal (Table 1 in the main report): (A) numerical weather prediction and land surface data assimilation, (B) terrestrial feedbacks in the climate-carbon system, (C) land-atmosphere interactions at regional scales, (D) regional and global carbon budgets, (E) water resources and hydrological feedbacks, and (F) integrated assessment. The application of CABLE in these research areas ranges from well-developed to emerging, so current resource levels for each area vary widely. CABLE development needs (Table 2) are largely cross-cutting, because science and infrastructure development is a foundation for work in many research areas.

The science embodied in CABLE has been developed over the last 20 years by the Australian research community, led initially by CSIRO and now including major contributions from the Bureau of Meteorology (through CAWCR) and several universities (particularly through the Centre of Excellence in Climate System Science, CoECSS).

CABLE has been extensively evaluated and tested against multiple data sources, including eddy fluxes over many ecosystems, streamflow and runoff, ecological data, and (coupled with atmospheric models) atmospheric CO_2 concentrations. This rigorous, community-wide testing process has led to demonstrable improvements in the performance of CABLE, and these improvements are expected to continue. The overall performance of CABLE against multiple tests is now comparable with the best land surface schemes used in the international community. This is a significant achievement, given that the breadth of applications for CABLE is far broader than for most alternative land models.

CABLE is now a community model, meaning that it is developed jointly by the Australian land surface research community and is owned scientifically by its community of developers. This brings three substantial benefits: (1) community access to advances by each participant, resulting in a better model than can be achieved by any group in isolation; (2) rapid identification and correction of scientific problems and coding errors; (3) enhanced uptake of CABLE and its embodied scientific knowledge across disciplines.

Realisation of the benefits of a community model requires good governance structures, open access to code, standardised benchmarking tests, technical support and effective communication between users. While CABLE already has rudimentary benchmarking and governance structures, the evolution and formalisation of these to allow efficient and impartial utilisation of community contributions to CABLE remains a key priority.

It is vital that CABLE continues to be supported and developed. It is independent of other land surface models world-wide and has been designed to meet both global and Australian-specific modelling needs. There has been significant investment in CABLE and it has a growing user base. There are major societal and policy drivers for land surface modelling, in weather forecasting, climate projection, water management, carbon management, environmental information and integrated assessment; the ability of the Australian land-surface research community to respond consistently to these drivers is dependent on using a high-quality Australian land surface model, CABLE, rather than an ad-hoc collection of overseas models.

Recommendations

Recommendation 1: That CABLE be maintained as a community model, developed jointly by the Australian land surface research community and owned scientifically by its community of developers. [Section 1.2, Section 6]

Recommendation 2: that high priority be given to the development of a more efficient coupling strategy to integrate CABLE more effectively into the UKMO Unified Model, to take advantage of UM upgrades and expedite the use of CABLE in NWP as well as in climate modelling. [Section 2.1.1, Section 4.1]

Recommendation 3: That CAWCR and the CSIRO Water for a Healthy Country Flagship explore appropriate mechanisms to share processes and technologies for code maintenance, technical user support, calibration and benchmark testing of CABLE and AWRA, to achieve (1) efficiencies, (2) functional improvements in both systems, and (3) consistency of overlapping outputs (particularly water balance fluxes). [Section 2.1.3, Section 5.1E]

Recommendation 4: That resources be provided by CSIRO and the Bureau, coordinated through CAWCR, to support further exchanges with land surface scientists in the UK Met Office, to facilitate the coupling between CABLE and the Unified Model. [Section 4.1]

Recommendation 5: That resources for CABLE development be allocated with recognition of the needs for both new CABLE development (model, code, benchmarking etc) and also for application and delivery of results from existing CABLE versions (V2.0 in 2012). [Section 5.1]

Recommendation 6: That CABLE management structure consist of (1) a CABLE management committee; (2) a technical support group and (3) a CABLE coordinator. [Section 6.1]

Recommendation 7: That the parties involved in the development of CABLE allocate resources to building the relationships and structures needed for effective community model development, including (a) version control and file sharing (using Apache subversion on a NCI machine), (b) standardised benchmarking procedures, (c) a dynamic website to facilitate communication, and (d) regular meetings. [Section 6.2, Section 6.4]

Recommendation 8: That CSIRO and CoECSS jointly explore licencing arrangements for CABLE IP that are consistent with the nature of CABLE as a community model, initially by evaluating the current licence. [Section 6.3]

Recommendation 9: That CSIRO be the agreed primary custodian of CABLE, and that CAWCR Management agree on an appropriate point of accountability within CSIRO and BoM for CABLE management and interactions with CoECSS and other partners. [Section 6.3]

INTRODUCTION

This report has been prepared at the request of the CAWCR Supervisory Committee to guide the development, implementation and uptake of the land surface model, CABLE, for the period 2012-2017. The Terms of Reference for the report are given in Box 1.

The report considers the needs of the primary stakeholders in CABLE; the Bureau of Meteorology, CSIRO and the University community. Science directions, technical developments and the requirements of CABLE as a community model are documented. In preparing this report, the writing team has drawn on a CABLE planning document prepared in February 2011 for DCCEE and notes from discussions at a CABLE workshop held in November 2011.

The sections of the report broadly follow the Terms of Reference, with minor reordering for clarity:

- Section 1, "Scope of CABLE", addresses the parts of ToR 1 concerned with the scientific motivation and scope of CABLE.
- Section 2, "Societal and policy drivers", addresses ToR 3.
- Section 3, "Achievements: evaluations and applications", addresses the parts of ToR 1 concerned with the evaluation and application of CABLE.
- Section 4, "Current development and implementation strategy", addresses ToR 2.
- Section 5, "Outputs and pathways", addresses ToR 4.
- Section 6, "Future management and governance", addresses ToR 5.
- Section 7, "Risks of not proceeding with CABLE", addresses ToR 6.

The relevant components of the Terms of Reference are reproduced at the start of each section.

A further note on structure is important at the outset. The report is largely built around three lists, each containing six items:

1. six societal and policy drivers (Section 2.1);
2. six research areas (Table 1, Sections 2.2 and 5.1);
3. six cross-cutting development needs (Table 2, Section 5.2).

The first list describes societal needs and drivers; the second describes the response of the research community to these needs, in terms that relate to the evolving research agendas of research organisations and teams; the third describes essential cross-cutting science and infrastructure development that is a foundation for the work of many teams. The second list emerges from the first, and the third from the second. Despite the coincidence that each list is six items long, the lists do not map exactly onto each other.

Purpose: To develop a 5 year road map for Community Atmosphere Biosphere Land Exchange (CABLE) model development and implementation

Background: CABLE has now been underway since 2006 and the purpose of this exercise will be to develop a new roadmap for the development, implementation, and uptake of CABLE for the period 2012-2017. The development of the CABLE roadmap should consider national and international science questions, and the requirements of the primary stakeholders, the Bureau of Meteorology, CSIRO, and the University community. This roadmap will be employed to inform the respective agencies of the national benefits accruing from the future activities. It should articulate high level options and associated science and technical requirements, proposed applications, including reference to how CABLE and other land surface modelling activities can achieve mutual leverage, the integration within ACCESS, requirements of a community model, as well as resources necessary for the realisation. The report will be provided to the CAWCR Supervisory Committee for their consideration and feedback in the first case but also will be expected to inform activities, inter alia, in WIRADA and other areas of CSIRO and Bureau R&D activity as appropriate.

Terms of Reference

1. Summarise the background scientific motivation for CABLE, the intended scope, achievements, and impact to date, benchmarked against international standards.
2. Review the current development and implementation strategy, highlighting the strengths and weaknesses, scope changes, and associated of relevance activities, governance and management, and key relationships.
3. Identify the underlying science and national policy drivers for further development along with the key needs and demands for CABLE over the period 2012-2017. Consideration should be given to national and international science questions, the role of CABLE, community expectations (including the community model concept), and outcomes of relevance to CSIRO, the Bureau, Universities, and other parties of relevance. This scope should address priorities relevant to weather, climate, water, carbon, associated environmental modelling (e.g., ACCESS) covering weather and climate timescales, and the mutual benefit to both the hydrometeorological and hydrological communities.
4. Identify clear outputs, and associated high level options to achieve these outputs. Include clear reference to capability and capacity requirements related to the science, observations, assimilation/initialisation, modelling, the associated support systems and relationships crucial to the intended progress. In this context related developments in land surface modelling e.g. AWRA-L, AWAP, JULES etc and ACCESS should be considered. Methods to optimise contributions and outcomes from the various players, as well as the advantages of working towards common approaches/frameworks should be expanded, including high level requirements for resources necessary to maintain existing commitments.
5. Report on options for future management and governance with particular attention to mechanisms (project oversight, project management, and technical advice) that will maximise the prospects of integration of CABLE with other initiatives, including ACCESS, hydrology modelling etc and realise national and international level outcomes.
6. Identify major science outcomes at risk if a second generation CABLE is not undertaken.

Box 1: Terms of Reference for the CABLE Roadmap.

1 SCOPE OF CABLE

ToR 1: Summarise the background scientific motivation for CABLE, the intended scope, achievements, and impact to date, benchmarked against international standards.

1.1 Scientific motivations for CABLE

The land surface is a crossroads in the Earth System, connecting many biophysical processes that determine flows of momentum, energy, water, carbon and other entities. Therefore, land surface modelling connects many communities: those working on components of the land-surface system (e.g. plant physiology, soil science, snow science) and also those for whom the land surface is part of a larger system, e.g. numerical weather prediction (NWP), climate, hydrology, carbon cycle and land-surface management communities. Each community makes extensive use of land surface models (LSMs), though with different priorities as to the processes that need to be modelled, their complexity and their temporal and spatial resolution. NWP, for example, prioritises the accurate simulation of surface energy and momentum fluxes, and related parameters such as albedo. Accurate initialisation of model land surface states such as soil temperature, moisture and snow is essential. For climate simulations, processes such as land use change become important as well as the interactions between climate and the carbon cycle. For the carbon community, land surface models contribute to quantifying terrestrial carbon budgets. For the water community, they help to understand the impact of water-climate-carbon feedbacks on water resources.

The Community Atmosphere Biosphere Land Exchange (CABLE) model was originally designed for climate applications, and is now moving into use for other major applications: carbon, water and NWP. As detailed below, CABLE has been extended and extensively tested for carbon cycle applications, both global and for the Australian continent. Hydrological and NWP applications are limited at this stage, but under development in ways outlined below.

CABLE is designed to run globally, and also to support more detailed applications on the scale of the Australian continent. The aim is that CABLE will perform as well as or better than other state-of-the-art global land surface models, especially for Australian applications.

1.2 Scope of CABLE

Land surface models (Figure 1) usually include four kinds of process: biophysical, biogeochemical, vegetation dynamics and disturbance. Biophysical processes include the exchange of momentum, water, and heat between the land surface and atmosphere as well as snow related processes. Biogeochemical processes describe the cycling of carbon and nutrients (nitrogen, phosphorus) between atmosphere, plant, detritus and soil pools. Vegetation dynamics include establishment, mortality, invasion and extinction. Disturbance includes fire (both natural and anthropogenic), land use change (e.g. clearing for crops) and land management (e.g. irrigation, fertilisation, offtake of harvested products). Land surface models may also simulate non-vegetated surfaces including ice, lakes and urban surfaces.

CABLE is intended as a state-of-the-art global land surface model, and, to some extent, includes each of these types of processes. At present, biophysical and biogeochemical processes are more fully developed than vegetation dynamics or disturbance.

CABLE can be run 'off-line' at a single location or across a domain (such as the Australian continent) using prescribed meteorological forcing, or it can be coupled to an atmospheric model that provides this forcing meteorology. CABLE is unusual, compared to other global land surface models, in the number and range of atmospheric models to which it has been coupled, including ACCESS, CCAM, TAPM, Mk3L, with WRF coupling underway. CABLE is also used in BIOS2, a high-resolution (5 km) framework for off-line modelling of coupled carbon, water, energy and nutrient (N and P) cycles, presently applied over the Australian continent. CABLE is written in Fortran 90.

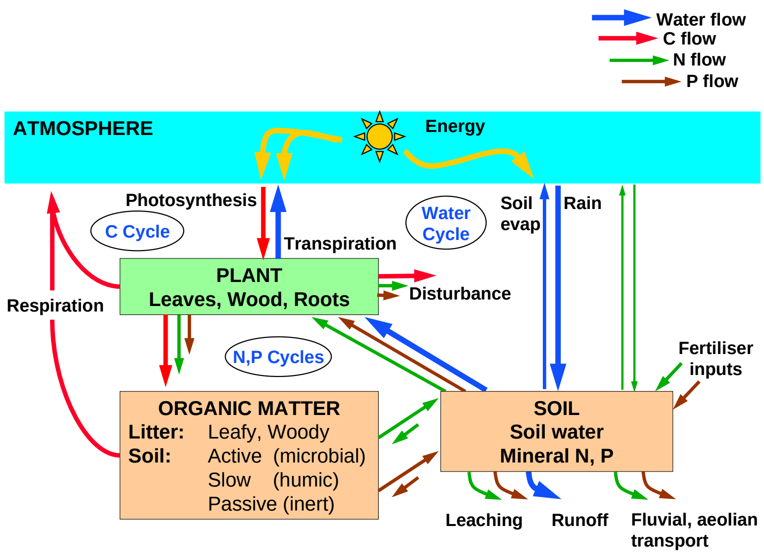

Fig. 1 Major flows and stores of energy, water, carbon and nutrients represented in a Land Surface Model (after Raupach et al.,2001).

CABLE is rapidly evolving into a community model, meaning that it is developed jointly by the Australian land surface research community and is 'owned' scientifically by its community of developers. This brings three substantial benefits: first, the community as a whole gains access to the advances made by each participant, so that the scope of any individual or institutional participant's research capacity is broadened and the communication and uptake of their research is actively assisted. Second, the broad developer and user base associated with a community model also means that inefficiencies or coding and documentation errors can be found quickly, delivering more reliable results in less time. Third, the community model approach enhances the uptake of CABLE and its embodied scientific knowledge across disciplines (e.g. NWP, climate, carbon cycle, hydrology). These benefits can only be realised with good governance structures, a transparent benchmarking procedure, open access to code, technical support and effective communication between users. Section 6 assesses how this might be achieved for CABLE.
As a community model, CABLE is now the land surface model of choice for virtually all Australian land-surface research groups (see Appendix 2). CABLE users are based in CAWCR, other parts of CSIRO and BoM, other Australian or state government agencies, and at eleven Australian universities. The Centre of Excellence in Climate System Science (CoECSS) is committed to using CABLE for much of its land-surface modelling work, and is also committed to making significant contributions to CABLE development and

technical support. There is also some use of CABLE by overseas groups including universities in China and USA and CSIR in South Africa.

Recommendation 1: That CABLE be maintained as a community model, developed jointly by the Australian land surface research community and owned scientifically by its community of developers.

1.3 CABLE development path

As described in Wang et al. (2011), the origins of CABLE lie in the land surface model developed at CSIRO for use in their climate model, and the merger of a number of prior developments. The history can be summarised briefly as follows:

- 1990: first CSIRO soil-canopy scheme (CSCS) developed. It had a single soil type, constant roughness length over land and no vegetation (Kowalczyk et al., 1991).
- 1993: explicit representation of vegetation added to CSCS using the big-leaf canopy approach (Sellers et al., 1986; Kowalczyk et al., 1994).
- 1995: CSCS soil module modified to include six soil layers and three snow layers.
- 1997: Separately, the Soil Canopy Atmosphere Model (SCAM), developed by Raupach et al. (1997), located the modelled canopy above the soil surface to allow for a more realistic aerodynamic coupling of land and atmosphere (Raupach, 1989) and also included a simple model for vegetation roughness length (Raupach, 1994).
- 1998: Again separately, Wang and Leuning (1998) developed a one-layer, two-leaf canopy model allowing the calculation of leaf energy balances and photosynthesis separately for sunlit and shaded leaves. Photosynthesis, stomatal conductance and the leaf energy balance are fully coupled using the semi-mechanistic leaf-level model presented by Leuning (1995). This canopy model was combined with the soil snow scheme from CSCS and was known as the CSIRO Biosphere Model (CBM) (Wang et al., 2001; Wang and Barrett, 2003).
- 2003: CSCS, SCAM and CBM were merged, producing the first version of the CSIRO (now Community) Atmosphere Biosphere Land Exchange Model (CABLE v1.0) (Kowalczyk et al., 2006, Wang et al., 2011).
- 2006: CABLE version 1.4b released to the science community.

Since that release, new improvements and developments have been made to CABLE. The new improvements are tiling of a land cell, the new classification of plant functional types based on the IGBP classification (Loveland et al. 2000) and spatially explicit soil parameters from the harmonized soil database (http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/). A new biogeochemical model, CASA-CNP (Randerson et al., 1996; Fung et al., 2005; Wang et al. 2010) has also been added to simulate carbon, nitrogen and phosphorus cycles in terrestrial ecosystems.

With the adoption of the UK Met Office Unified Model as the atmospheric component of ACCESS, work began on coupling CABLE v1.4b to the UM, to replace the Met Office Surface Exchange System (MOSES). Initial work was with UM6.3, with current coupling work using UM7.3, focussed on providing an ACCESS version with CABLE v1.4b to participate in the Coupled Model Intercomparison Project (CMIP5). An initial coupling was ready for testing in late 2009. Work has continued since to improve the coupling interface and to ensure compatibility between offline, ACCESS and Mk3L versions of CABLE. Mk3L provides a low resolution coupled ocean-atmosphere model environment for testing CABLE developments.

The imminent version of CABLE (version 2.0) provides consistency in its science routines across both the off-line and ACCESS versions of CABLE, and includes the developments noted above (tiling, CASA-CNP etc.). CABLE v2.0 is currently being benchmarked for release in mid. 2012.

2 SOCIETAL AND POLICY DRIVERS

ToR 3: Identify the underlying science and national policy drivers for further development along with the key needs and demands for CABLE over the period 2012-2017. Consideration should be given to national and international science questions, the role of CABLE, community expectations (including the community model concept), and outcomes of relevance to CSIRO, the Bureau, Universities, and other parties of relevance. This scope should address priorities relevant to weather, climate, water, carbon, associated environmental modelling (e.g., ACCESS) covering weather and climate timescales, and the mutual benefit to both the hydrometeorological and hydrological communities.

Because the land surface is a crossroads in the Earth System, there are multiple societal and policy drivers for land surface modelling. In Section 2.1 we identify six such drivers, together with the value proposition for CABLE involvement, the institutional stakeholders, and the key relationships. The six drivers are (1) weather forecasting, (2) climate change projections, (3) water resources management, (4) carbon management and accounting, (5) environmental information and accounting and (6) integrated assessment. In Section 2.2 we identify the implications for CABLE science and development pathways, by identifying broad research goals in six research areas: (A) numerical weather prediction and land surface data assimilation, (B) terrestrial feedbacks in the climate-carbon system, (C) land-atmosphere interactions at regional-scale, (D) regional and global carbon budgets, (E) water resources and hydrological feedbacks, and (F) integrated assessment. A more detailed analysis of outputs and pathways in these research areas is given in Section 5.

2.1 Drivers

2.1.1 Weather forecasting

Major societal and policy drivers: There is a strong societal need for accurate and continually improving weather forecasting services at time scales from sub-daily to seasonal, for the general public and for specific purposes (e.g. aviation, agriculture, water supply, emergency warning). The importance of land surface modelling as a component of NWP models for these purposes is well recognised.

Value propositions for CABLE: provision of better land-surface initial conditions, particularly for soil moisture, and better descriptions of land-atmosphere sensible and latent heat fluxes and the land-surface radiation balance.

Institutional stakeholders and key relationships: The major institutional stakeholder is BoM, with the Bureau and CSIRO, working together through CAWCR, as the key institutional route for delivery of science from the Australian land surface community. The primary host NWP model is the UK Met Office Unified Model (UM).

A major issue is model coupling. As discussed in more detail elsewhere (Section 4.1, Section 5.1A), CABLE is the land surface model in ACCESS, Australia's climate model based on the UM, but not in the BoM NWP model based on the UM, because coupling CABLE into the UM to replace the UKMO land surface scheme (JULES) has been technically challenging and time consuming. There are three reasons why this replacement is desirable.

- Australian NWP should use a land surface model (CABLE) that recognises key differences between Australian and typical northern hemisphere biomes, such as: the dominance of semi-arid conditions; the ensuing high importance of soil evaporation (accounting for ~50% of all water loss from the Australian continent, Haverd et al., 2012a); responses of most perennial vegetation to drought rather than seasonality; nutrient responses evolved to suit nutrient-depleted soils; the importance of ground water interactions and deeply-rooted vegetation, leading to long hydrological response times.

- Use of CABLE makes available to the NWP a rigorously tested land surface scheme for Australian biomes (see Section 3.1 for examples).
- Use of CABLE ensures consistency of land surface modelling between NWP, climate and other arenas discussed below that depend on weather and climate forecasts, including water, carbon and environmental information and management, and integrated assessment.

Recommendation 2: that high priority be given to the development of a more efficient coupling strategy to integrate CABLE more effectively into the UKMO Unified Model, to take advantage of UM upgrades and expedite the use of CABLE in NWP as well as in climate modelling.

2.1.2 Climate change projections

Major societal and policy drivers: As with weather forecasting, there are strong societal and policy needs for progressively improving climate change projections, with ongoing improvements in confidence and reductions in uncertainties.

Value propositions for CABLE: improvements to descriptions of (a) changes in terrestrial energy and water balances, (b) the terrestrial carbon balance and its implications for the land CO_2 sink, (c) CO_2 and nutrient feedbacks that modulate water and carbon exchanges (for example by potentially limiting the land CO_2 sink), (d) human modification of these processes by land use change, (e) the roles of land surfaces in the atmospheric dynamics of non-CO_2 greenhouse gases (CH_4, N_2O and others), and (f) the roles of land surfaces in non-gaseous radiative forcing, including albedo changes and regional modification of cloudiness and cloud feedbacks on energy balances.

Institutional stakeholders and key relationships: The major Australian stakeholder is the Australian community, through the Australian Government and several Government Departments (primarily DCCEE but extending to departments with responsibilities for environment, water and energy resources, and also to DFAT and the Department of Prime Minister and Cabinet). Many State Government departments with similar portfolios are also stakeholders, and there is a continuing demand from local governments for climate change projections and information.

CAWCR is the primary BoM-CSIRO structure for linking with these stakeholders. Climate change science, with a focus on land surface interactions, is delivered through CSIRO's Marine and Atmospheric Research Portfolio.

2.1.3 Water resources management

Major societal and policy drivers: Water policy in Australia has been transformed by the 2004 National Water Initiative of the Commonwealth Government, leading to the formation of the Water Division in BoM, now merged into a Climate and Water Division. One of its primary responsibilities is the provision of accurate national water accounts and water resource assessments, a function supported by several water balance modelling frameworks developed in CSIRO. These include the Australian Water Resources Assessment (AWRA) modelling suite: AWRA-L (land), AWRA-R (river) and AWRA-G (groundwater), together with the AWAP (Australian Water Availability Project) model, a predecessor to AWRA that is still in active use.

The AWRA system is currently used only for retrospective estimation although potential applications for season to multi-decadal forecasting and evaluating management scenarios have been flagged by BoM. Regardless, any water balance model needs to be provided with rainfall analyses, forecasts or long-range projections from NWP or climate models. Because water and energy balances share a common evaporative or latent heat flux, there is a need to ensure that the land surface models in NWP, climate and water resources management are hydrologically consistent. This does not mean using the same model for all these applications, because of different requirements in different applications (for example in space-time resolution and coupling with other models). It does require inter-model comparison and harmonisation where necessary.

Value proposition for CABLE: ensuring consistency of AWRA and CABLE (as the land surface component of NWP and climate models).

Institutional stakeholders and key relationships: Key stakeholders are Commonwealth and State Governments, through the Council of Australian Governments (COAG). Science is delivered primarily through the Climate and Water Division of BoM, the CSIRO Water for a Healthy Country Flagship, and the CSIRO-BoM research alliance, WIRADA. Other Government agencies, prominently the Murray-Darling Basin Authority, are also important stakeholders. Further research linkages exist through regional climate-water research programs such as SEACI (the South East Australian Climate Initiative) and IOCI (the Indian Ocean Climate Initiative). CAWCR is already a major research provider to these initiatives, with CABLE playing an important role in assessing (for instance) the sensitivity of regional water balances to climate variability and change through the effects of temperature, CO_2 and land use change.

Recommendation 3: That CAWCR and the CSIRO Water for a Healthy Country Flagship explore appropriate mechanisms to share processes and technologies for code maintenance, technical user support, calibration and benchmark testing of CABLE and AWRA, to achieve (1) efficiencies, (2) functional improvements in both systems, and (3) consistency of overlapping outputs (particularly water balance fluxes). [Section 2.1.3, Section 5.1E]

2.1.4 Carbon management and accounting

Major societal and policy drivers: Carbon management in the terrestrial biosphere requires carbon accounting at an accuracy sufficient to monitor biophysical outcomes of actions, and compliance with commitments. Carbon accounting therefore has several policy meanings: (1) verifying compliance with existing international agreements on greenhouse mitigation, particularly the Kyoto Protocol (KP), and (2) development of frameworks for full carbon or greenhouse gas accounting, involving a much wider set of processes, that can contribute realistically to mitigation commitments.

Value proposition for CABLE: to support full carbon accounting, especially by determining likely effects of climate change on full carbon accounts.

Institutional stakeholders and key relationships: The National Carbon Accounting System (NCAS) was set up in DCCEE (formerly the AGO) mainly to verify Australia's progress towards its Kyoto targets, particularly the offsets from reductions in land clearing that were claimable under KP Article 3.7. NCAS therefore has highly developed methods for tracking land use change and its carbon consequences at fine space scales and relatively coarse (annual and longer) time scales. NCAS does not provide a full terrestrial carbon balance in the sense required for full carbon accounting, presently being focussed on regions and processes relevant to its primary purpose. Carbon cycle science is primarily delivered through CSIRO's Marine and Atmospheric Research Portfolio and the Australian Climate Change Science Program (ACCSP).

2.1.5 Environmental information and accounting

Major societal and policy drivers: There are increasing calls at Government levels, and in many sectors, for environmental information systems that can support comprehensive or "triple-bottom-line" (economic, environmental, social) perspectives on societal goals. These require comprehensive environmental accounts that recognise common-pool environmental assets, stores and fluxes (such as water, carbon and nutrient stores in landscapes), the biophysical and ecological functionality that maintains these pools, and the resilience of landscape functionality to potential disturbances and shocks like climate change, extreme weather events, fire and land use change.

Value proposition for CABLE: application of a terrestrial mass and energy balance framework to this endeavour.

Institutional stakeholders and key relationships: A new Environmental Accounting Branch in the Climate and Water Division of BoM is charged with developing ways of establishing and maintaining an environmental information system for Australia, including comprehensive environmental accounting. At the time of writing (May 2012), discussions between this Branch and representatives of the CABLE community have already established that CABLE has high potential in this domain.

2.1.6 Integrated assessment

Major societal and policy drivers: Integrated Assessment is the development of global or regional future scenarios that account for multiple interacting factors, including

- biophysical processes (climate, water, ecosystems, …);
- resource availabilities (food, minerals, fossil fuels, …);
- economic development (growth patterns, production and consumption shifts, …);
- technological changes (efficiency improvements, new technologies, …);
  geopolitical shifts (emergence of developing-world powers, …)

Value proposition for CABLE: better incorporation of the interactions between land-surface biophysical processes and climate, productive land use, and ecosystem services.

Institutional stakeholders and key relationships: In CSIRO, the Integrated Carbon Pathways (ICP) program is the main vehicle for developing a capability in Integrated Assessment Modelling (IAM). CABLE is not yet coupled with prototype IAMs in ICP (GIAM and NIAM, at global and national scales respectively). However, there is a desire in ICP to explore the possibility of such coupling. For an IAM, CABLE would offer advanced modelling of coupled landscape water, carbon and nutrient dynamics.

2.2 Research areas and goals

The above societal and policy drivers lead to broad research areas and goals for CABLE development over the period 2012-2017. We identify six major priority areas, each with a broad goal for CABLE development, as shown in Table 1. These areas are analysed in detail below (Section 5.1), by identifying the rationale for research, key component tasks, and capability and resource implications.

The research areas clearly intersect: A, C and E have a focus on physical climate while B and D concern carbon and related biogeochemical cycles. Area F is integrative. Some areas focus on global issues, some on Australia, and some span spatial scales.

There is a partial but far from exact correspondence between the research areas in Table 1 and the six drivers identified in Section 2.1, together with their primary institutional stakeholders. This derives in part from the different research goals of stakeholder organisations, but also reflects a tendency for research projects to be institutionally based and led, and from the largely separate histories of institutions. This structural aspect of CABLE research is unlikely to disappear in the short term, and it has both benefits and challenges. The benefit is a strong institutional commitment to and leadership for particular research areas; the challenge is ensuring that CABLE developments are coordinated and shared across the CABLE community. We address this challenge in Section 6.

The research areas and goals in Table 1 are consistent with science questions and priorities for land surface modelling identified in recent Australian analyses:

- 'Australian Climate Change Science. A National Framework' (http://www.climatechange.gov.au/en/publications/science/cc-science-framework.aspx) notes in its Section 3.1 the need for terrestrial carbon cycle research such as "a greater focus on how rising temperatures, changing moisture availability, and altered fire regimes, for example, will affect the ability of vegetation and the land surface to take carbon out of the atmosphere and store it". In its Section 3.2 the Framework states "Elements of the climate system affecting Australia that require focussed attention via process studies include ... land surface-atmosphere exchange and the dynamic role of vegetation interacting with changing climate."
- The Australian Academy of Sciences report "To Live within the Earth's limits" (Gifford et al., 2010) identifies (on p34) the challenges facing terrestrial models as including:
    - Simulation of terrestrial processes at local and regional scales (e.g. representation of land cover change, urban landscapes, irrigation, groundwater coupling).
    - Appropriately configuring terrestrial models for different applications – weather forecasting, seasonal projection, decadal and century-scale projection.
    - Assimilating observational data into terrestrial models.
    - Improving hydrological modelling, including radiative transfer, surface–groundwater interactions, and stomatal response to various stresses.

In Section 5.1 we identify the ways that these challenges are addressed within the research areas and goals in Table 1.

Table 1 Research areas and broad science goals for CABLE development. Specific outputs and pathways for these broad goals are spelt out in Section 5.1.

	Research area	**Goal**
A	*Numerical weather prediction and land surface data assimilation*	To ensure that CABLE can be used in ACCESS for numerical weather prediction (NWP)
B	*Terrestrial feedbacks in the climate-carbon system*	To ensure that CABLE has the key capabilities required for assessing carbon-climate-nutrient feedbacks in global earth system simulations
C	*Land-atmosphere interactions at regional scales*	To ensure that regional atmospheric forcing by the land surface, and the response by the land surface to regional drivers (meteorological and climatological) are adequately represented in CABLE
D	*Regional and global carbon and nutrient budgets*	To ensure that CABLE provides credible estimates of the terrestrial components of regional and global carbon and nutrient budgets, for analysis of carbon-climate-human interactions
E	*Water resources and hydrological feedbacks*	For CABLE to support credible prediction of water-climate feedbacks, for CABLE to produce consistent water balance and consequently energy balance, to support climate water balance impact assessment
F	*Integrated Assessment*	To apply CABLE in Integrated Assessment Modelling, in support of emerging major initiatives (in CSIRO and wider) such as the Integrated Carbon Pathways (ICP) program

3 ACHIEVEMENTS: EVALUATIONS AND APPLICATIONS

ToR 1: Summarise the background scientific motivation for CABLE, the intended scope, achievements, and impact to date, benchmarked against international standards.

This section surveys research achievements with CABLE to date, covering seven different evaluations of CABLE (Section 3.1) and five applications (Section 3.2).

There have been approximately 42 papers published that present science that directly depends on CABLE, or where CABLE has been involved in a model intercomparison (Appendix 3). Other papers rely on atmosphere model simulations that include CABLE as the land surface component of the model, but without being focussed on land-surface research (e.g. Patra et al., 2011).

A key achievement of CABLE is that it functions inside several coupled model environments, particularly Mk3L, CCAM, TAPM and ACCESS, as well as off-line at site-level, regional and global contexts – one important regional-scale implementation being the BIOS2 framework for application at 5 km scale across the Australian continent. This diverse functionality enables evaluation and benchmarking against multiple data sets, comparison with many other models, and a wide range of applications.

3.1 Benchmarking and Evaluation

Here we present seven examples of benchmarking and evaluation of CABLE, drawing from work by several different groups. The examples use CABLE for single sites, regional offline applications and coupled to different atmospheric models.

3.1.1 Benchmarking against statistical models

Abramowitz et al. (2008) included CABLE amongst a set of land surface models in a study which benchmarked their flux predictions at single locations against those of statistical models using only meteorological data. As demonstrated in Figure 2, CABLE performance was similar to other land surface models, while all land surface models generally under-performed compared with the statistical models. This type of bench-marking test is useful for highlighting weaknesses in process-based models, in particular where meteorological information used in their inputs is being under-utilized.

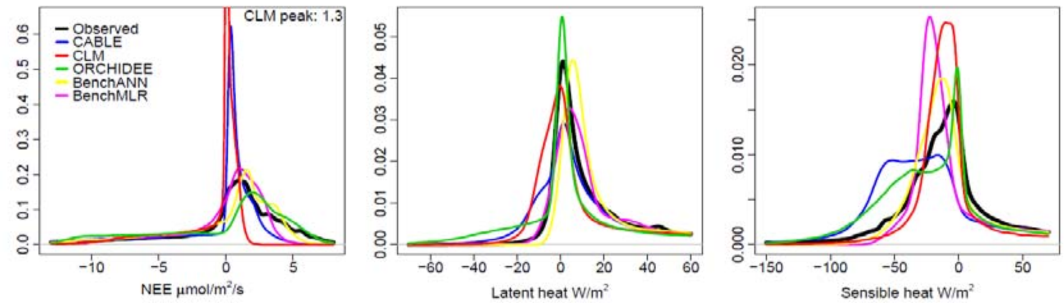

Fig. 2 Probability density functions for each LSM and benchmark model for the three fluxes considered, over all six sites. Note that where distribution tails are not visible, they dissipate uniformly. (Taken from Abramowitz et al. 2008, Fig 2)

3.1.2 Multiple constraints from eddy fluxes, streamflow and ecological data (RECCAP)

Haverd et al. (2012a) explored the utility of multiple data sets to constrain estimates of Australian carbon and water cycles, using CABLE hosted in BIOS2 (a framework for off-line modelling of coupled carbon, water, energy and nutrient cycles for Australia at 5 km resolution, using regional soil, vegetation and meteorological inputs). Data sets included observations of streamflow from several hundred gauged catchments, eddy flux measurements of ET and NEE (net ecosystem exchange of carbon), litter-fall data, and data on carbon pools. It was shown that all data types provided useful constraints, and that eddy flux measurements (Figure 3) provided a tighter constraint on primary productivity than the other data types. Results for mean Australian net primary productivity are better constrained than an ensemble of 12 previous continental estimates, and are mid-range among these estimates.

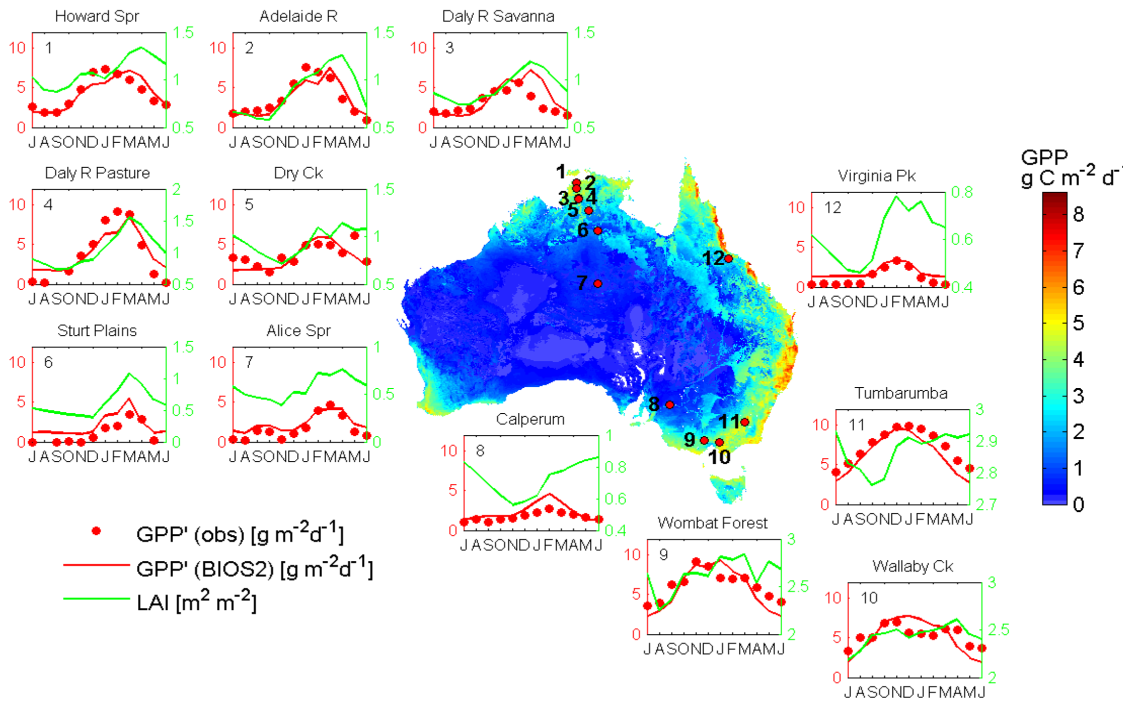

Fig. 3 Spatial distribution of gross primary productivity (GPP) (1990-2011), as simulated using CABLE in BIOS2, and seasonal cycles of modelled and observed GPP (and remotely sensed LAI) at 12 OzFlux sites

3.1.3 Evaluation of evapotranspiration (WIRADA)

The Water Information Research and Development Alliance (WIRADA) evaluated the performance of a number of actual evapotranspiration (ET) products for Australia (King et al., 2011a and b). Evaluation was conducted using flux tower observations and catchment water balance over a 6-year period. Among the ET estimation methods examined was the variant of CABLE that used the soil-litter (SLI) scheme of Haverd and Cuntz (2010). The investigation revealed regions of the continent where the CABLE actual ET estimates performed well, noticeably in the tropics with an abundance of water and energy, and regions where there may be room for improvement (e.g. water limited areas).

3.1.4 Evaluation of total runoff in Australian catchments (WIRADA)

Viney et al. (2012) compare and contrast eight models for estimating streamflow generation across Australia, including five spatially explicit conceptual rainfall-runoff models and three continental scale land surface or landscape hydrology models, including an earlier version of CABLE (v1.4 with an early version of SLI). Predictions were assessed against observations of streamflow in 408 unimpaired catchments across Australia. The level of calibration was quite different: the conceptual rainfall-runoff models were calibrated to data from the nearest catchment, whereas the continental models used a single set of parameters for the entire continent. The rainfall-runoff models all gave similarly good predictions and performed better than continental models including CABLE. However, it was demonstrated that calibration of a single continental set of AWRA parameters achieved benchmark performance (Viney et al., 2012) and the same may well hold for CABLE.

3.1.5 Evaluation of total runoff in large basins

A recent study (Zhou et al., in press) compared the simulated mean annual runoff from 150 large basins globally by 14 global land surface models and 6 Budyko-type models, forced with two different precipitation datasets. They showed that CABLE performed better than most other land surface models in all three performance measures, model bias, correlation between modelled and observed mean annual runoff and Nash-Sutcliffe Efficiency.

3.1.6 Evaluation against atmospheric CO_2 data

Law et al. (2006) coupled an early version of CABLE with the CCAM atmospheric model and assessed the resulting 20th century carbon-climate simulation against atmospheric CO_2 data. The simulation followed the protocol for C4MIP phase 1, which was a modelling experiment designed to test the biospheric component of coupled climate-carbon simulations. It was demonstrated that CO_2 concentrations on a range of time scales (from diurnal cycles to long-term trends) were useful for diagnosing errors in simulated fluxes. Figure 4 demonstrates model evaluation using the observed seasonal cycle of CO_2 concentrations.

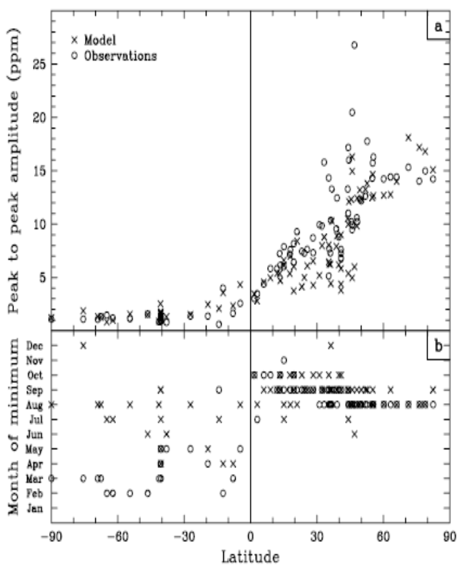

Fig. 4 Peak-to- peak amplitude of the seasonal cycle (a) at observing sites and the month of the minimum concentration (b) for the model (x) and observations (o). (From Law et al., (2006), Figure 5).

3.1.7 Carbon fluxes and climate in CSIRO Mk3L climate model

Mao et al. (2011) produced a detailed analysis of the global carbon fluxes and climate simulated with CABLE coupled with the CSIRO Mk3L climate model. They reported the effects of replacing the original simple land surface model in Mk3L with CABLE. The impact on simulated climate variables was small but favourable. Of more significance, the incorporation of CABLE allowed Mk3L to simulate carbon cycle variables, e.g. net primary productivity (NPP). Figure 5 illustrates an evaluation of Mk3L global NPP against predictions from independent global off-line carbon cycle models.

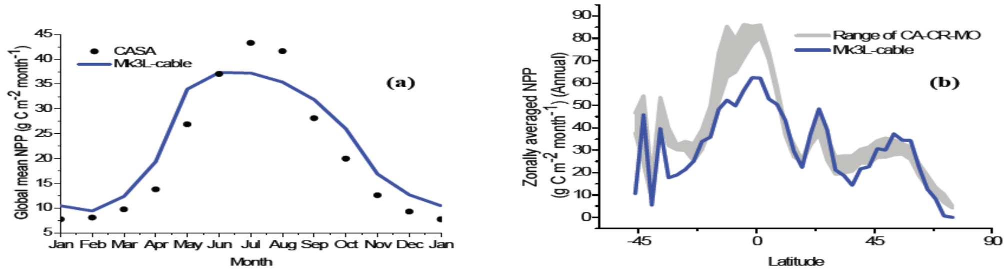

Fig. 5 Net primary productivity (g Cm^{-2} $month^{-1}$) for (a) global mean values compared with the estimate from CASA (Randerson et al.,1997); (b) annual net primary productivity simulated by Mk3L-CABLE compared with the range of estimates from CA (Randerson et al.,1997), CR (Cramer et al., 1999) and MO (Zhao et al., 2005). (From Mao et al., 2011, Figure 9).

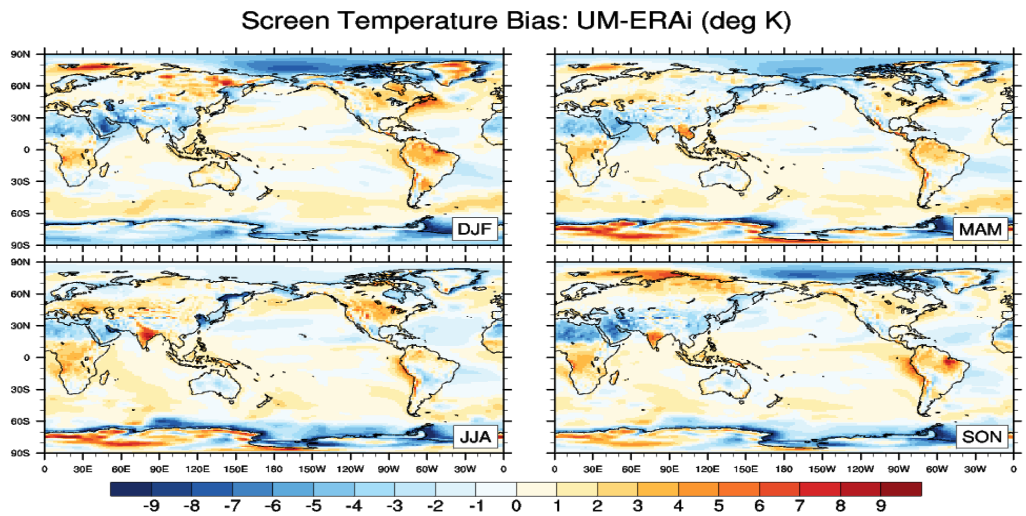

Fig. 6 Difference between ACCESS1.3 and ERA-Interim screen level temperature for 1979-2005 for each season, Dec-Feb (top left), Mar-May (top right), Jun-Aug (bottom left), Sep-Nov (bottom right).

3.2 Applications

We summarise five examples of applications of CABLE, drawing from work by several different groups.

3.2.1 ACCESS submissions to CMIP5

ACCESS submissions to CMIP5 include those with CABLE as the land-surface component of the model (ACCESS 1.3). Figure 6 compares modelled and observed screen temperature for 1979-2005 from the historical simulation of ACCESS1.3. Sparsely vegetated regions are often too cold, while regions where precipitation is underestimated (e.g. India in the monsoon season) are too warm. The current ACCESS1.3 implementation is derived from CABLE v1.4b. Future work will update this to CABLE v2.0, allowing the land carbon cycle to be simulated.

3.2.2 Influence of nitrogen and phosphorus cycles on terrestrial CO_2 uptake

Zhang et al. (2011) used the Mk3L model with CABLE to estimate the influence of nitrogen and phosphorous cycles on terrestrial CO_2 uptake under increasing CO_2 concentration from 1870 to 2009. They found that nitrogen limitation on carbon uptake strongly reduces the global terrestrial carbon sink, while the phosphorous has a smaller impact globally (Figure 7) but significant regional effects.

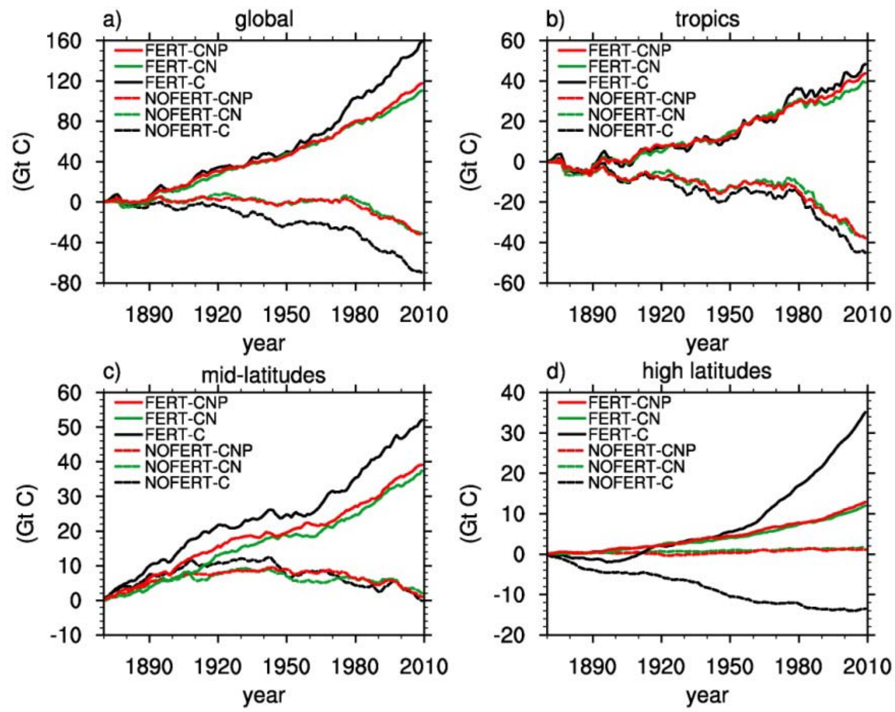

Fig. 7 Change in terrestrial carbon (Gt C) for (a) global land; (b) tropical regions (22°S - 22°N); (c) Northern Hemisphere mid-latitudes (29°N - 51°N); and (d) Northern Hemisphere high latitudes (51°N - 90°N). Solid lines are with CO_2 fertilization enabled, dashed lines are with CO_2 fertilization ignored. C, CN and CNP represent simulation of the MK3L model with CABLE for carbon cycle only, carbon and nitrogen cycle or carbon, nitrogen and phosphorus cycles. (from Zhang et al. 2011)

3.2.3 CO_2 monitoring at the CO2CRC Otway Project

Luhar et al. (2009) applied CABLE-TAPM to CO_2 monitoring at the CO2CRC Otway Project in south-west Victoria, Australia's first demonstration of deep geological storage of CO_2. CABLE-TAPM simulates the Otway meteorology and fluxes well (Fig 8), and could therefore be used to quantify flux-transfer and dispersion processes, and contributions from various sources and sinks that influence CO_2 concentrations at Otway.

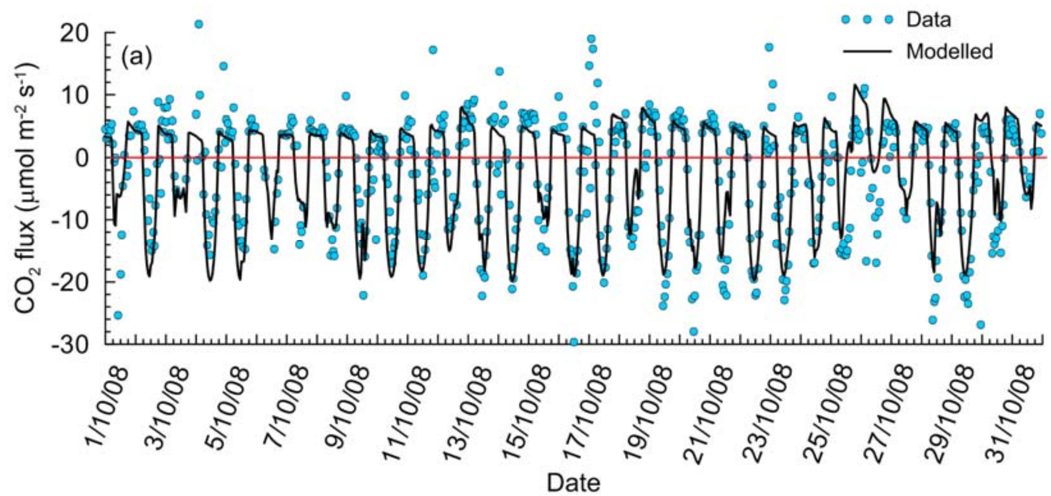

Fig. 8 Comparison of the observed and modelled CO_2 fluxes using TAPM with CABLE for October 08 at Otway. (From Luhar et al. 2009)

3.2.4 Carbon balance for the Australian continent (RECCAP)

Haverd et al (2012b) provide an assessment of the carbon balance for the Australian continent for the period 1990-2011, forming part of the global REgional Carbon Cycle Assessments and Processes (RECCAP) project. High spatial resolution bottom-up estimates of the biospheric fluxes were obtained using CABLE (in BIOS2) and compared with independent estimates from 5 dynamic global vegetation models. Bottom up estimates of other terms in the carbon budget were obtained from existing local and global products, permitting construction of a complete continental carbon budget, presented in Figure 9. A key result was that the interannual variability of NBP is comparable with Australia's entire emissions accounted under the NGGI (Fig 9, lower right).

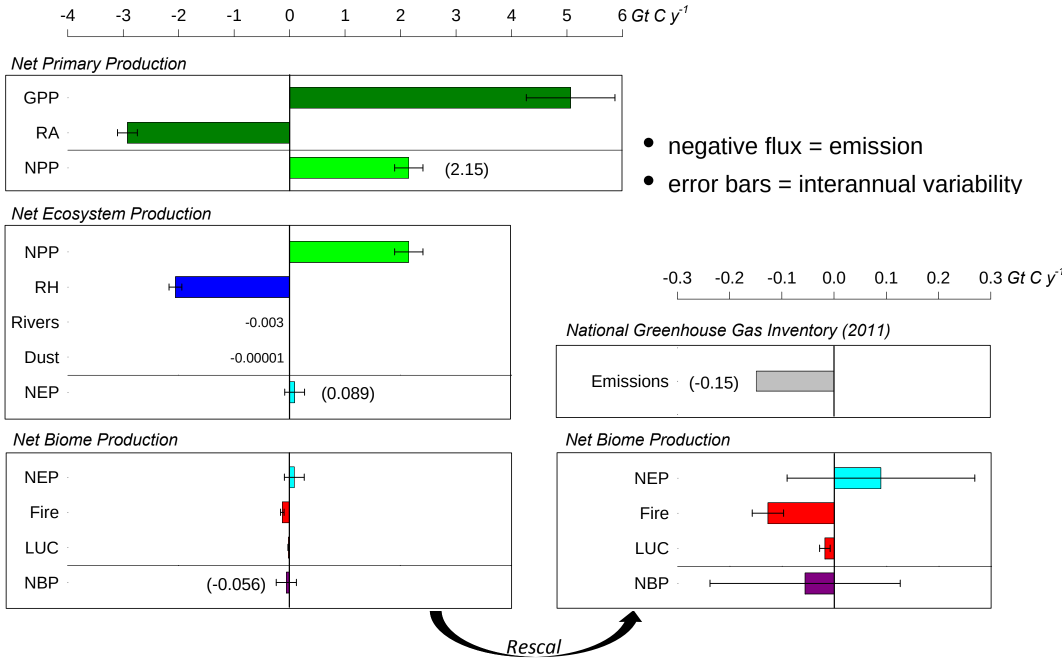

Fig. 9 Mean carbon budget for Australia (1990-2011). Negative fluxes represent emissions. Error bars indicate interannual varaiability (range for LUC, otherwise 1 σ). The National Green House Inventory Emissions include non-CO_2 contributions (0.025 Gt C(eq) y^{-1})

3.2.5 Effect of land cover change on regional temperatures

Pitman et al. (2011) used CABLE inside the CSIRO Mk3L climate model (assessed by Mao et al. 2011) to assess how and why land use and land cover change (LULCC) affects regional temperature under increased greenhouse gases. Their main conclusion was that changes in rainfall and snow caused by increases in CO_2 dominate how LULCC affects climate, thereby necessitating climate models to correctly locate changes in rainfall and temperature relative to LULCC.

4 CURRENT DEVELOPMENT AND IMPLEMENTATION STRATEGY

ToR 2: Review the current development and implementation strategy, highlighting the strengths and weaknesses, scope changes, and associated of relevance activities, governance and management, and key relationships.

4.1 Current strengths and weaknesses of CABLE

Representation of processes: CABLE was one of the first global land surface models to adopt the two-leaf approach to take account of the effect of diffuse radiation on canopy photosynthesis and one of the few models to explicitly represent the within-canopy turbulence. This makes it suitable for simulating air chemistry within a plant canopy. Since being coupled to CASA-CNP, biogeochemical processes are now also well represented; CABLE is one of only two global models known to include both nitrogen and phosphorus nutrient cycles. In independent evaluation studies, CABLE's performance compares well with other well-respected land surface models (e.g. Abramowitz et al, 2008).

Weaknesses in process representation include CABLE's representations of leaf phenology and land use change; they remain simple in comparison with some international models. Establishment and mortality of vegetation is not represented in CABLE. CABLE simulates ice surfaces, but lake and urban schemes are not yet formally part of CABLE. Some of these limitations are being addressed in application-specific versions of CABLE, highlighted in Sec 3.2.

Standardised benchmarking: A significant weakness in the current development process is that there is not yet a standardised procedure for benchmarking against multiple data types. Such a procedure is required urgently to enable efficient and objective assessment of updates to CABLE code. This would include both point-based and distributed evaluation of radiation, runoff, evapotranspiration and carbon fluxes and stores, for example. One approach to the resolution of this issue is discussed in Sections 5.2(i) and 6.2 below.

Incorporation into other modelling systems: The diversity of CABLE's applications – its implementation in a variety of different atmospheric models, as well as use as a stand-alone model, particularly in the BIOS2 framework for the Australian continent – is a clear strength. It means that CABLE is used to answer a broad range of science questions across many fields and organisations. It also poses a number of technical challenges. The first is that of code management and the desire to maintain common core science code amongst all the implementations of CABLE (see Sec 6.2). In particular, investment in bench-marking across applications is vital for transferring science developments in one application of CABLE to other models/applications, and the resources required for this should not be underestimated.

The second challenge is managing different development timelines for CABLE and its host models. New versions of the UM are usually released about three times a year. The Bureau of Meteorology currently uses UM7.5 for operational global NWP, the Met Office uses UM7.9 operationally and the ACCESS climate model is based on UM7.3. Coupling CABLE into UM7.3 has been a time-consuming process, in part due to structural limitations of the UM (e.g. number of vegetation types) which were not appropriate for CABLE. This long coupling time has been the major reason for not testing CABLE in the

BoM NWP system. In addition, since UM7.6, the default UM land surface model has changed from MOSES to the Joint UK Land Environment Simulator (JULES, Best et al. 2011). JULES is scientifically very similar to MOSES2 but is, like CABLE, being developed as a community land surface model. A more efficient coupling strategy is required to integrate more effectively with JULES and to take advantage of UM upgrades. Recent work on the CABLE interface code (data structure, modularity etc) should contribute to more efficient coupling.

These requirements lead to Recommendation 2 (already foreshadowed in Section 2.1.1) and Recommendation 4:

Recommendation 4: That resources be provided by CSIRO and the Bureau, coordinated through CAWCR, to support further exchanges with land surface scientists in the UK Met Office, to facilitate the coupling between CABLE and the Unified Model.

A diverse and motivated developer community: CABLE developers belong to many different organisations and have many different research priorities. With appropriate management structures (see Section 6), the potential for this community to enhance CABLE's scope and performance is considerable. With the addition of the CoECSS as well as other university investments in ecological research, CABLE's developer community is larger than it has ever been. Ensuring that the key modelling and scientific advances of this growing community are incorporated into CABLE is essential.

4.2 Recent developments and changes

Recent developments of CABLE have typically been for specific applications, motivated by different groups' research and funding priorities, and this is unlikely to change. The list below outlines some very significant recent advances in CABLE development, yet these risk being lost if CABLE's governance structure cannot provide the mechanisms for them to be integrated into the core CABLE code available to all researchers (a topic we revisit in more detail in Section 6). Developments of note include:

a) Soil-Litter-Iso (SLI) (Haverd and Cuntz, 2010) is an isotopically enabled hydrologic scheme, suitable for use as part of an isotopically enabled land surface model. It models coupled transport of heat, water and stable isotopes (HDO and $H_2^{18}O$) in soil and litter. SLI has been used to partition evapotranspiration between its component fluxes (Haverd et al., 2011) and has been coupled to CABLE v1.4 and implemented and tested in BIOS2 for Australian continental off-line simulations. SLI will not be in CABLE 2.0 as it must first be tested globally, both off-line and in a coupled environment, but it is intended for use in later versions of CABLE

b) CASA-CNP: The CASA-CNP model has recently been implemented into CABLE. CASA-CNP is the only global biogeochemical model with C, N and P cycles. It has been calibrated against various estimates of soil C, N, litter C, plant C (Wang et al., 2010). It has been used offline in an international study comparing predictions by different biogeochemical models against observations from free air CO_2 experiments (FACE) (B. Medlyn, pers. comm.), and, coupled to Mk3L, in a study of the change in nutrient limitation from 1850 to 2100 (Zhang et al., 2011). Work on implementing CASA-CNP into CABLE in ACCESS is in progress with initial test runs completed. This is one step towards ensuring full earth system simulation capability in ACCESS.

c) Land use and land cover change (LULCC): the biophysical and biogeochemical effects of LULCC on climate have recently been implemented and tested in CABLE coupled to Mk3L. Pitman et al. (2011) used this system to investigate the interplay between LULCC and background climate when examining regional climate. Mk3L with CABLE was also used by Avila et al. (2012) to investigate temperature extremes in LULCC scenarios. It has additionally been used to study the effects of land cover change from 1850 to 2100 on climate and permissible CO_2 emissions from 2006 to 2100 (Zhang et al., unpublished). The implementation of LULCC in all these cases was relatively simple and further development will be required for future work.

d) Urban and lake schemes have been developed for CCAM to run alongside CABLE and account for non-vegetated surfaces. The lakes scheme has been ported to ACCESS but work remains on how non-vegetated surfaces are best integrated into CABLE.

e) The nature of the soil respiration representation in CABLE was compared against a wide range of other representations by Exbrayat et al (in review), who found that while CABLE's parameterisation performed as well as any other, all approaches were very sensitive to the representation of model soil moisture, which varies widely across models.

f) Parallel version of offline CABLE. In collaboration with the CSIRO high performance computing team, we have developed a trial parallel version of offline CABLE running on 4 processers but need to generalise this to run on larger numbers of processors. This is critical for offline simulations over large domains and where many simulations are required such as for parameter estimation or other applications.

g) Carbon allocation. An alternative carbon allocation scheme for forest ecosystems based on biomass allometry (Wolf et al., 2011) has been implemented into CABLE. The allometry-based allocation scheme simulates the relative proportions of leaf, wood and root better than the present allocation scheme for forest ecosystems (Dai, pers. comm.).

h) A recent study by Wang et al. (2012) has shown that correlations among leaf traits can provide a significant constraint on the simulated global gross primary production and likely latent heat fluxes. However it still is unclear how the correlations will be taken into account in future CABLE simulations

i) A land surface model benchmarking facility, the *Protocol for the Analysis of Land Surface models* (PALS, pals.unsw.edu.au), is being developed for the offline (uncoupled) component of CABLE's benchmarking. In the first iteration of this web application (online now), forcing and flux evaluation data from around 50 flux tower sites is available, as well as automated evaluation of uploaded model outputs using a variety of variables and metrics. Later phases of PALS will include distributed runoff, albedo and other remotely sensed data experiments.

j) CABLE is coupled to LiS and through LiS to WRF. This enables simulations to be conducted at 50 km through to 1 km resolution over Australia with CABLE, but also with several other land models all coupled to several planetary boundary layer models. The code is running in test mode at NCI. Evaluation of the modelling system, which is only preliminary at present, suggests simulations of up to a decade provide very good results, significantly better than those with alternative land models.

Of these advances only CASA-CNP (b) is currently planned for release as part of CABLE v2.0. To ensure these developments become part of future CABLE releases, the governance issues outlined in Section 6 (with recommendations) should be of the highest priority and resources need to be allocated to facilitate appropriate bench-marking of each development. The CABLE-LiS system is subject to both the CABLE licence and the LiS licence. This enables the code to be released to researchers affiliated with the CoECSS, which is a large subset of the CABLE community. The CABLE-WRF coupling can be made freely available to all with a CABLE licence but to have CABLE made part of WRF such that it can be developed as part of that modelling system would require CABLE to be made much more freely available.

4.3 Current governance structure

Until recently CABLE had no governance structure and CABLE development was driven by project needs, and more recently by ACCESS developments. Those interested in using CABLE for research and non-commercial use have been able to access the CABLE code by registering as a user and signing a license agreement (Appendix 4). With increasing numbers of CABLE users across a range of institutions, it was recognized early in 2011, that a CABLE governance structure would need to be implemented. Discussions were held between CAWCR and university scientists and general agreement was reached on a proposed governance structure, including how CABLE code could be managed and updated. These proposals were described and discussed at a CABLE workshop in late 2011 and there appears to be broad community agreement to proceed. Details are given in Section 6, noting progress to date in implementing these plans.

4.4 Key relationships

As a land surface model, CABLE is a tool. Key relationships considered in this subsection encompass those who manage and develop CABLE, the community of CABLE users, providers of datasets for model input or validation, and the custodians of larger modelling systems of which CABLE is one component. Relationships with policy and institutional stakeholders are analysed in Section 2.

4.4.1 CABLE managers and developers

Management of CABLE originated in CSIRO, currently resides with CAWCR and, as a community model, will need future university involvement. CABLE developers are principally within CAWCR and CoECSS, but this may change over time. The interplay between these two groups is key to CABLE's success as a community model. CABLE's management structure requires significant investment and development to be able to leverage the broad range of scientific advances made by CABLE developers. The lack of this investment to date has meant many significant improvements made to CABLE have not been integrated into the core CABLE code. Section 6 is dedicated to structuring a solution to this problem.

4.4.2 CABLE users

CABLE users span a wide range of Australian and international universities and government agencies (including parts of CSIRO and BoM outside CAWCR). As this is a large group working in a broad range of environments, its capacity to provide evaluation of CABLE beyond its benchmarking framework (as defined by developers) as well as finding "bugs" or inconsistencies in CABLE's implementation is extremely important for CABLE as a stable community model. For this engagement and feedback to be meaningful and constructive, CABLE management in turn needs to provide users with clearly demarcated model versions through periodic version controlled code releases as well as maintaining up-to-date documentation of CABLE's scientific and coding evolution.

4.4.3 CABLE dataset providers

CABLE relies heavily on its input datasets. The performance of CABLE depends on the quality of its input and calibration datasets. At global scale, many of those datasets come from international compilations (e.g. IGBP, the harmonized world soil database, ISLSCP II, GSWP2, GPCC). Quite often different datasets are available for similar inputs, such as meteorological forcings. Understanding the strengths and weaknesses of each dataset is important for assessing the performance of CABLE. The most complete dataset for surface characterization (vegetation types, soil texture types) was compiled for ISLSCP II and is available for download freely. Other more specialized dataset, such as land cover and land cover change datasets may differ among different modeling groups. For ACCESS simulations CABLE uses the interpretation of the land cover change dataset from Hurtt et al. (2011) by the National Center for Atmospheric Research (NCAR, USA). Given the work involved in compiling datasets for land surface models, relationships with other modelling groups are valuable for sharing datasets.

Over the last decade or so, more gridded global data products have become available for validating or calibrating global models, such as the flux products from the FluxNet communities, and global soil data from the harmonized world soil data base. Collaboration with some major institutions and participation in major model inter-comparisons are very important for CABLE to share the latest global datasets and to address major science questions.

For Australian applications, Australian datasets are critical especially for simulations at higher spatial resolution. Consequently a key relationship is with TERN facilities (www.tern.org.au), particularly eMAST (Ecosystem Modelling and Scaling Infrastructure), AusCover (Australian biophysical map products and remote sensing data time-series) and OzFlux (a network of towers around Australia with continuous measurement of CO_2, water vapour and energy exchange between the terrestrial ecosystem and atmosphere).

CABLE is also used for studying processes at individual sites. The most commonly available datasets are from FluxNet communities, such as OzFlux where hourly or half-hourly meteorological forcing and surface fluxes are measured, and can be directly used in CABLE. Other datasets include the observations from the manipulated field experiments, such as soil warming experiments and Free Air CO_2 Experiments (FACE). Many of those experiments have been carried out in USA and Europe, and therefore close collaboration with those overseas institutions will help us to improve the performance of CABLE.

4.4.4 Modelling system custodians for which CABLE is a component

As noted in Sec 1.2.1, CABLE is a component of many atmospheric or coupled modelling systems including ACCESS, CCAM, Mk3L and TAPM with developing links to LIS and WRF. While the key relationships represented by these modelling systems are currently CAWCR and CoECSS, providing CABLE as an optional part of CCAM opens CABLE usage to organisations such as CSIR (South Africa) and the Philippine, Indonesian and Vietnamese Met services. Likewise coupling CABLE to LIS and WRF may also expand the CABLE user base. Maintaining common science code across CABLE versions in different models has been challenging. This is addressed in Section 6.2. CABLE also has to be able to cope with developments in the models to which it is coupled. Of particular note is the relationship with the UK Met Office because of the use of the UM as part of ACCESS. A recent visit by a UK Met Office land-surface scientist to CSIRO has been very valuable and this type of scientist exchange should be encouraged (Recommendation 4, already foreshadowed in Section 4.1).

4.4.5 International scientific linkages

Land surface science needs nationally are also mirrored internationally – indeed, the challenges around CABLE are shared by many other major land models and a key rationale for building CABLE in the future is to be able to contribute to internationally first class science. There are multiple levels of international science to which CABLE is relevant:

- At the largest scale, the land community has not been particularly effective in analysing CMIP3 and CMIP5 data and the science that can be assessed in terms of land surface modelling for AR5 is, at best, limited. Resolving challenges in this area as they relate to CABLE provides another opportunity for Australian leadership on the international stage.

- CABLE is usefully represented on the GLASS (Global Land/Atmosphere System Study) Panel of GEWEX (Global Energy and Water Cycle Experiment). Gab Abramowitz and Andy Pitman are members of the GLASS panel and this helps enhance the international profile of Australian science through CABLE.

- The LUCID (Land-Use and Climate, IDentification of robust impacts) project has been fundamental to progress in how land cover change affects climate. CABLE has been closely involved in all stages of LUCID – first with CCAM and then with Mk3L. This places us in a strong position to use LUCID science to parameterize LULCC in ACCESS.

- There is a strong push internationally for developing and applying standardised tools for benchmarking the performance of different global land surface models. One such initiative is International Land Model Benchmarking (ILAMB; www.ilamb.org; Luo et al., 2012) which aims to build on C-LAMP (http://www.climatemodeling.org/c-lamp) and has significant support within the global land surface modelling community. A complementary initiative, the Protocol for Analysis of Land Surface models (PALS; www.pals.unsw.edu; Abramowitz, 2012) aims to incorporate ILAMB evaluation metrics into an online system that allows immediate benchmarking against other models. As PALS is being developed in Australia, it additionally contains Australian data sets and will be used as part of the benchmarking suite for CABLE.

- Some very important GLASS projects (http://www.gewex.org/glass_panel.html) are not being done in Australia due to lack of capacity. An example is GLACE-2 which is critical since it suggests that semi-arid regions may be particularly strongly coupled to the atmosphere. However, all GLACE and GLACE-2 work was northern-hemisphere specific and Australia needs to lead in GLACE-related work to develop a southern hemisphere capacity. University researchers working with CAWCR may undertake experiments similar to GLACE-2 and strong management around CABLE is extremely important as it enables work with CABLE to feed-back into ACCESS and other CABLE stakeholders

- Another important GLASS project is LoCo. The coupling of CABLE into LIS and WRF may enable LoCo science to be undertaken in collaboration with overseas groups supported by University researchers working with CAWCR. Again, strong management around CABLE is extremely important to permit this work to feed-back into ACCESS.

5 OUTPUTS AND PATHWAYS

ToR 4: Identify clear outputs, and associated high level options to achieve these outputs. Include clear reference to capability and capacity requirements related to the science, observations, assimilation/initialisation, modelling, the associated support systems and relationships crucial to the intended progress. In this context related developments in land surface modelling e.g. AWRA-L, AWAP, JULES etc and ACCESS should be considered. Methods to optimise contributions and outcomes from the various players, as well as the advantages of working towards common approaches/frameworks should be expanded, including high level requirements for resources necessary to maintain existing commitments.

5.1 Goals, rationale and component tasks

In Section 2.1 we characterised six societal and policy drivers for CABLE research, and in Section 2.2 we identified an ensuing set of six broad research areas and goals for CABLE development over the period 2012-2017 (Table 1). In this section, the research areas in Table 1 are analysed in detail, by identifying the rationale for research, key component tasks, and capability and resource implications.

Some component tasks can be addressed with CABLE in its current form while others require further development. CABLE developments required for one research area are, in many cases, of benefit to other research areas. For this reason potential CABLE developments are consolidated into one list, in Section 5.2.

The resources available to undertake research with CABLE in each of these research areas are linked with the extent to which CABLE is currently used in that research area. Where the use of CABLE is well established, there are generally sufficient resources to continue that use; where it is proposed that CABLE usage be introduced to a research area, current resources may be insufficient to make significant use of CABLE. Resource issues specific to each research area are noted below.

Recommendation 5: That resources for CABLE development be allocated with recognition of the needs for both new CABLE development (model, code, benchmarking etc) and also for application and delivery of results from existing CABLE versions (V2.0 in 2012)

A.   Numerical weather prediction and land surface data assimilation (DA)

Goal: To ensure that CABLE can be used in ACCESS for numerical weather prediction (NWP)

Research rationale: The land surface states such as soil moisture, temperature and snow play an important role in land atmosphere coupling. Soil moisture and temperature have a significant impact on screen level temperature and humidity, low clouds and precipitation, (e.g. Dharssi et al. 2009). The land surface is also very important for the seasonal prediction of extreme events such as heat waves and drought (Weisheimer et al. 2011). A state of the art, physically based land surface model is needed to meet a number of NWP developments including (a) the development of high (1.5 km) resolution NWP systems, for which convection is explicitly modelled (Steinle and Dharssi 2011), (b) operational assimilation of satellite soundings over land and the consequent challenge of estimating the land surface emissivity, (c) ensemble prediction systems (EPS) are increasingly being used for NWP and DA but with little effort made to perturb the land surface states of the EPS, resulting in a detrimental impact on forecasting skill (Sutton et al. 2006). The use of two or more land surface models for EPS might allow for significant improvements.
Data assimilation is critical for NWP since errors in the model initial conditions can grow rapidly and seriously degrade forecasts. Land surface DA is also important but few near real-time ground-based observations of soil moisture and temperature are available for initialising model soil states and indirect observations are usually used by land surface DA (Dharssi et al. 2011; de Rosnay et al. 2009). In addition, model soil moisture values are highly model specific, precluding the direct transfer of soil moisture values from one land surface model to another (Koster et al., 2009) and requiring satellite derived surface soil moisture to be bias corrected for the land surface model being used by a NWP system (Reichle et al. 2004; Reichle and Koster 2004). The existing ACCESS land surface DA schemes are designed to work with MOSES2 and JULES. Significant modifications would be required for the ACCESS land surface DA schemes to work with CABLE. Inconsistencies in the analysed land surface fields could introduce spurious, long-lived, shocks to the NWP system and degrade forecasts.

Component tasks:

- Documentation, including a planning paper and technical report describing trials and results
- Coupling of CABLE into the versions of the UM used at BoM for operational NWP
- Development of a CABLE based land surface data assimilation scheme based on the current JULES based scheme. Account for differences between CABLE and JULES model structure (tiled soil in CABLE), file formats and soil moisture climatologies.
- Improvements to CABLE required for NWP (see Sec 5.2)
- Trialling of CABLE in the Bureau's NWP systems (global, Australia wide, city). This is computationally expensive and will likely take at least a year. Cheaper off-line comparisons between JULES and CABLE (using FluxNet and GSWP2 data) would be a useful first step.
- Verification of NWP forecasts against screen level and precipitation observations

Capability and resources: Leadership and land surface DA capability to come from CAWCR-BoM. Additional land surface DA capability also resides in CMAR, CLW and Melbourne and Monash Universities (Peter Rayner, Jeff Walker). CAWCR-CMAR will provide the land surface modelling expertise, and, with possible help from CoECSS, will couple CABLE to JULES.

*B.	Terrestrial feedbacks in the climate-carbon system*

Goal: To ensure that CABLE has the key capabilities required for assessing carbon-climate-nutrient feedbacks in global earth system simulations.

Research rationale: Human activities have significant impacts on climate through directly emitting greenhouse gases into the atmosphere, and indirectly by changing the amount of energy absorbed by the land surface and its partitioning, and the carbon balance of land ecosystems. It is important to quantify these human influences on the global climate-carbon system, focussing here on terrestrial forcings and feedbacks at global scale. To account for these forcings and feedbacks, earth system models are being developed to include fully interactive carbon and other biogeochemical cycles and the effects of land use and land use change on the surface energy balance and partitioning, and carbon balance.

Component tasks including assessing and improving CABLE's performance:

- in centennial-scale ACCESS simulations (with carbon cycle) such as those specified for CMIP5
- in lower resolution earth system model simulations suitable for sensitivity testing. Mk3L currently meets this need but consideration may need to be given to a low resolution version of ACCESS for longer-term needs.
- in simulations focused on understanding the impacts of land use and land-use change
- in ACCESS simulations used to interpret atmospheric measurements of greenhouse gases
- by optimizing CABLE parameters using atmospheric CO_2 and surface flux CO_2 data in multi-year runs, to improve carbon cycle simulations in climate prediction
- by including other feedbacks, such as other greenhouse gases, aerosols and biogenic volatile organic compounds (BVOCs), which can affect regional and global climate and be affected by climate change. With appropriate developments to CABLE, ACCESS could be used to explore aspects of these feedbacks linked to land surface processes.

Capability and resources. Leadership and capability in this area are focused in CAWCR-CMAR, primarily in Earth System Modelling (ESM) but with links into the greenhouse gas measurement activities of Atmosphere and Land Observation and Assessment (ALOA). There is significant expertise on land use and land use change with CoECSS, while CABLE parameter estimation is being developed at the University of Melbourne (Rayner). Given the history of CABLE involvement in this area, this work is adequately resourced for undertaking new science based on the current CABLE version. Recent work has benefitted from visiting students and researchers from China under the exchange program between the Chinese Ministry of Education and Chinese Academy of Sciences and CSIRO and Australian Universities, and opportunities such as this should continue to be utilized.

C. Land-atmosphere interactions at regional scales

Goal: To ensure that regional atmospheric forcing by the land surface, and the response by the land surface to regional drivers (meteorological and climatological) are adequately represented in CABLE.

Research rationale: (a) Understanding what drives regional and local climate and how the land surface responds to larger-scale drivers; (b) Impacts, adaptation and mitigation research focussed on land surface quantities, including how climate change affects streamflow, net primary productivity, soil moisture, fluxes of energy, water and carbon, extremes of temperature, rainfall etc.; how the terrestrial surface can be managed to mitigate the impacts of climate change and climate variability.

Component tasks are essentially in two categories:

(i) Development and testing of explicit representations of land-based drivers of the atmosphere that need to be resolved regionally (and applied globally) including:

- human-induced changes in vegetation (deforestation, reforestation);
- representation of unique characteristics of Australian vegetation in CABLE;
- agricultural landscapes, including irrigation;
- urbanisation;
- fire;
- groundwater transpiration interactions
- active soil carbon management;
- non-CO_2 (CH_4, N_2O) greenhouse gas emissions and vegetation emissions of biogenic volatile organic compounds (BVOCs).

(ii) Further development and evaluation to ensure that terrestrial system responses to atmospheric drivers in CABLE are appropriate. These include:

- a standardised evaluation environment that can assess CABLE's state variable responses to atmospheric drivers including interception, snow, soil moisture, runoff, heat storage etc, including the tailoring of existing observational products for this purpose;
- development and refinement of these process representations in CABLE where this testing indicates CABLE is either performing poorly or not commensurable with existing observational data products that offer valuable evaluation potential;
- the coupling of CABLE to the planetary boundary layers (PBLs) in host models,
- an assessment of how CABLE's coupling strength may affect its representation of these processes.

Capability and Resources. Leadership and capability in this area is focused in the CoECSS, particularly in its Program 3, 'Role of land surface forcing and feedbacks for regional climate'. Contributions from CAWCR come mostly from the intersection of this research area with research areas A, B, and D.

D. Regional and global carbon and nutrient budgets

Goal: To ensure that CABLE provides credible estimates of the terrestrial components of regional and global carbon and nutrient budgets, for analysis of carbon-climate-human interactions

Research rationale: At scales from landscape to global, major research questions are raised by anthropogenic changes to the cycles and budgets of carbon as CO_2, other GHGs (methane, N_2O etc), and nutrients (N and P). Anthropogenic influences occur directly through land use change (deforestation and afforestation), land management (for cropping, grazing and forestry), resource inputs (fertiliser application, irrigation) and also through pest and weed control. Questions include (a) quantitative understanding of the budgets of CO_2, other GHGs and nutrients, to characterise the spatial and temporal patterns of fluxes and stores, including mean, variability and extremes; (b) attribution of changes in budget patterns to drivers including rising atmospheric CO_2, past clearing, changes in nutrient regimes, and change and interannual variation in major climate drivers (precipitation, temperature and humidity); (c) design of greenhouse gas accounting frameworks including questions such as the relationship between anthropogenic and natural components of accounting frameworks, the implications of interannual variability, and the capacity of terrestrial carbon sequestration to meet Australian GHG target reductions; and (d) design of environmental accounting systems to allow tracking of changes in Australia's environmental capital, expressed in terms of the quantified functionality of carbon, nutrient and water cycles.

Component tasks involve

- implementation of fully functioning carbon and nutrient cycles in CABLE to allow the development of regional carbon and water budgets of the Australian continent (both hindcasts over the last few decades and projections under AR5 scenarios), using both off-line (BIOS2) and coupled online approaches;
- adequately representing Australian vegetation and soil in CABLE;
- improvement of the scheme for allocation of assimilated carbon between leaf, root and wood pools, by introducing dynamic allocation of carbon using ecological optimality hypotheses (Raupach 2005)
- determining the response of Australian vegetation to seasonal drought and inter-annual climate variation;
- determining the response of Australian ecosystems to fires and land cover change

Capability and resources. Leadership and capability in this area come from CAWCR-CMAR, particularly the ALOA group based in Canberra. Given the common focus on carbon between this research area and B, it is vital that common development needs are well coordinated. There is a strong link to the Global Carbon Project, particularly through the international RECCAP project. One (soon two) CSIRO OCE post-docs contribute in this area, and consideration needs to be given to whether this level of resource needs to be maintained at the end of their terms.

E.   Water resources and hydrological feedbacks

Goal: For CABLE to support credible prediction of water-climate feedbacks, for CABLE to produce consistent water balance and consequently energy balance, to support climate water balance impact assessment

Research rationale: Current generation hydrological models are being used to evaluate the implications of climate change and human disturbances on water resources availability and use. However, these models are limited or at least uncertain due to the inability to consider water cycle-climate feedbacks. CABLE in ACCESS could help address these limitations while a closer collaboration between CABLE and existing efforts in hydrological modelling, could make CABLE outputs more relevant to water resources management.

Global hydrological models produce predictions that do not consider possible feedbacks to the climate system, such as changes in rainfall recycling associated with land cover change or potential circulation changes associated with evapotranspiration from irrigation or wetland areas. Such changes may result in significant feedbacks on regional and even global precipitation and meteorological drivers of the hydrological cycle. Assessing these potential feedbacks requires a GCM with a land surface model (i.e. CABLE) that has defensible representations of ecohydrological processes and human modification of the water cycle. Hydrological process representation may be simpler than used in water resources models (e.g. without full surface or groundwater balance) but more sophisticated in other important ways, such as stomatal conductance, water use efficiency and carbon-nutrient interactions. Consequently there is value in benchmarking CABLE hydrology against historical reanalysis products derived from regional (e.g. AWRA) and global hydrological models. This leads to Recommendation 3 (already foreshadowed in Section 2.1.3). It is believed that this can lead to considerable efficiencies and very likely will lead to functional improvements in both systems and a slow convergence in model conceptualisation and code that makes formal merging of the code base feasible in the medium term.

In the medium-term, it may be possible to derive acceptable water resource predictions from CABLE-ACCESS directly, (e.g. streamflow generation and groundwater recharge), by adjusting the calibration and perhaps structure of CABLE against observations and correcting for the spatial scaling and bias issues in GCM meteorological variables (precipitation in particular). Calibration is possible by engineering an adapter for calibrating CABLE within the AWRA model high performance computing calibration system, thus exposing CABLE to a range of Australian and global hydrologically relevant observations.

Component tasks would involve:

- Model diagnosis and benchmarking, comparing CABLE to hydrological observations and more specialised models (e.g. AWRA). The PALS infrastructure offers an excellent opportunity for this.
- Engineer an adapter that would allow CABLE to be calibrated to hydrological observations using the AWRA model high performace computing calibration system.
- Evaluate GCM sensitivity to global and regional large scale changes in surface water evapotranspiration through irrigation and wetland changes.
- Evaluate GCM sensitivity to realistic or actual global and regional large scale changes in vegetation cover, such as those occurring in the Amazon and China.
- Modify hydrological process descriptions as required to achieve better agreement with hydrological observations (see Sec 5.2 for suggestions).

Capability and resources. CMAR (Canberra group) and CLW (Canberra group).

F. Integrated Assessment

Goal*:* To apply CABLE in Integrated Assessment Modelling, in support of emerging major initiatives (in CSIRO and wider) such as the Integrated Carbon Pathways (ICP) program.

Research Rationale*:* Major questions are now being asked at Government level about the holistic management of the intersections between carbon, water, energy and other sectors in Australia (e.g. PMSEIC 2010). These questions call for scientific assessment of the tradeoffs between the uses of landscapes for water production, agricultural production, and carbon sequestration (among other uses and ecosystem services), and the ways that these tradeoffs will be affected by climate change and other anthropogenic factors. The contribution of CABLE to this domain is to provide the best available modelling tools, encapsulating the best possible biophysical science, to answer questions such as:
(a) How will climate change affect the water use efficiency of Australia's vegetation, and thence the water yields of its catchments, through combined responses to CO_2 buildup (CO_2 fertilisation of plant growth), temperature (warming), changed rainfall patterns, and changed nutrient dynamics and inputs?
(b) What is the cost in regional water yields of terrestrial carbon sequestration in forests and agricultural soils? How will this cost change in response to factors mentioned in (a)?
(c) What is the attainable potential for terrestrial carbon sequestration to contribute to Australia's climate mitigation effort?
(d) What is the effect of climate variability on the above potentials and tradeoffs?

Component tasks:

- In conjunction with work on carbon budgets (D) and water budgets (E), develop tools for coupling CABLE with broader ICP Integrated Assessment modelling frameworks.
- Develop a small suite of specific project proposals to answer questions listed in (a), and explore collaborations and funding needed to make these projects happen.
- Benchmark CABLE against models which focussed on sectoral components e.g. agriculture, forestry

Capability and resources: Since this is a potential application for CABLE rather than a current use, it would require bringing together capability from a range of groups, and likely some new resources. Leadership would most likely rest with the Canberra CMAR group working on CABLE, in conjunction with the Canberra IAM group.

5.2 CABLE development needs

As noted above (Section 5.1), CABLE development needs are often common across a number of different research areas, though with different levels of priority. It is vital that any CABLE development is engaged with the range of potential users and applications for that development, so that development is integrated rather than duplicated. It is particularly important that CABLE development done to enable regional science specific to Australia is also built into, and used, in the global (ACCESS) context.

A logical approach to meet these needs is to identify CABLE cross-cutting development needs that are common across a number of research areas and to set up formal or informal working groups drawn from researchers across the research areas to both plan and implement any given CABLE development. Table 2 identifies a set of six cross-cutting development needs to be facilitated in this way.

This approach ensures that all potential users of a new development are involved in its design and would minimise the risk that a development for one research area could not easily be taken up by another. It is particularly important that CABLE development done for a regional application can be applied in a global context.

The CABLE community also needs to be alert to possible parallel developments in different modelling systems, such as AWRA, so that expertise and resources can be shared when appropriate (Recommendation 3).

CABLE development needs are diverse. Some tasks can be clearly defined, such as the porting of a piece of code from one CABLE application to the core CABLE code. Other tasks are open-ended, with many possible solutions depending on the complexity required or the resources available. An example might be representing urban landscapes. A simple urban scheme might be implemented relatively quickly but as research needs develop, and models increase in spatial resolution, additional research questions will emerge and additional capacity will be required.

Most global land surface models are following similar development paths. In the list below, we note only those developments that CABLE is linked with, and consequently where this might influence our development choice.

A clear process for the uptake of CABLE developments into the core CABLE code is critical. This requires a commitment to coding standards, comprehensive documentation and benchmarking model performance and the resources necessary to ensure this happens effectively (see also Section 6). Given the underpinning role of bench-marking, developments in this area are listed first and should be a high priority. The listed technical developments also include high priority tasks, either because they are prerequisites for some science developments or applications or because they consolidate previous application-specific CABLE developments into the core CABLE code. Science developments can and will happen in parallel depending on the interests and resources of the contributing teams, and consequently are less easily prioritised at this time. Most developments will be led by CAWCR and/or the CoECSS. Other contributions are listed against individual tasks.

We recommend that the CABLE Coordinator (Section 6.1) has responsibility for maintaining community-wide interactions to facilitate developments in the clusters in Table 2.

Table 2 CABLE cross-cutting development needs that are common across a number of research areas, with tasks to be addressed by formal or informal working groups drawn from researchers across multiple research areas

Development need	Development tasks
1. Benchmarking	• Identify datasets (forcing, evaluation and parameter constraining) required for CABLE offline benchmarking (flux tower, global albedo, global and continental runoff, etc) • Identify appropriate metrics (means, trends, correlation, probability density, time and spatial scales) for benchmarks using these datasets. • Develop benchmarking scripts incorporating these metrics • Integrate them into the PALS system (this means that all developers have access to the benchmarking facility, and can perform all offline tests themselves before submitting changes to the management committee) • Develop a standard AMIP style ACCESS run for benchmarking purposes, identifying which model output is critical for CABLE assessment. Collaboration should be sought with the climate metrics being developed by the ACCESS model evaluation team
2. Technical	• Ensure logical consistency and numerical stability of CABLE code • Integrate soil-litter-isotope (SLI) scheme into core CABLE code • Finalise coupling of CASA-CNP to CABLE in ACCESS and test appropriateness of parameter values • Re-assess within canopy turbulence based on technical note by I. Harman • Coupling of CABLE into JULES standalone code for DA testing • Couple CABLE into UMv8.2 or above, based on experience coupling CABLE into JULES standalone code • Ensure code structure adequately meets the needs of all users, for example, parameters need to be easily accessed by data assimilation applications • Improve modularity of the code, as required, and ensure core code is common across all host atmospheric models and standalone version • Explore the benefits and costs of implementing a formal land surface coupler

3. Land/biome representation	• Evaluate lake scheme in ACCESS, including re-evaluation of interface with CABLE and suitability for NWP applications • Represent Australian vegetation types of significance • Represent agriculture, irrigation etc. The first step is to implement a crop model from another global LSM such as Orchidee, SiB or JULES and evaluate for Australian applications. Links with integrated assessment models need to be explored. • Represent urban landscapes well. The first step is to port the urban scheme developed for CCAM to ACCESS and to assess its suitability for a range of applications including NWP. JULES urban schemes (M. Hendry) or work from Kings College, London (S. Grimmond) may also be useful. Ultimately, resolving how to represent urban landscapes in regional models, at multiple scales, to enable exploration of a range of planning, impacts, water questions etc is an area deserving of a research centre. • Evolve CABLE to represent savanna systems better. Monash (J. Beringer) is a possible contributor in this area. • Incorporate a model for wetlands into CABLE. Applications include regional simulations for SE Asia applications and for generating methane emissions. • Develop or import parameterisations for peatlands and permafrost.
4. Disturbance	• Include land cover change properly. This would extend work done in CABLE for Mk3L and is likely an on-going challenge, for 1-2 scientists, as developments in CABLE continuously require a revision of how land cover change should be represented. • A fire model is required to account for carbon fluxes and changes to the land surface following fire. Other ACCESS applications may also need to simulate fire but may have different requirements for model complexity. This should be assessed before any development work on fire is commenced. New work is beginning on fire for Australian carbon applications and integration with global needs should be considered.
5. Water	• Allow vegetation-ground water coupling in some regions. Some preliminary research is underway in the CoECSS but this is a very challenging problem that needs a better-integrated team across the national research community. • Modify hydrological process descriptions as required to achieve better agreement with hydrological observations. Target processes might include ecohydrological processes (rainfall interception evaporation, parameterisation of seasonal phenological strategies, deep soil and groundwater uptake by deep-rooted vegetation), rainfall-runoff response, soil and groundwater release. Input from WIRADA and the hydrology groups at Monash University and University of Melbourne would be valuable for setting priorities and providing potential parameterisations.

6. Carbon/vegetation dynamics	• Improve representation of phenology. Input from Macquarie University (S. Harrison) is possible in this area • Include dynamic allocation of carbon using the ecological optimality hypothesis • Restructure biogeochemical model to include vertical resolution of fluxes and stores in soil • Include major soil nitrogen cycle processes (eg nitrification, denitrification, nitrogen fixation) important to the terrestrial N_2O flux and also nitrogen limitations on the carbon cycle, extending present CASA-CNP formulations • Extend current enabling of CABLE for stable isotopes (^{18}O, ^{13}C and others) to enable model evaluation/calibration against paleoclimate data and atmospheric isotopic data. • Include fluxes of other radiatively important gases and aerosols including CH_4, black carbon, biogenic volatile organic compounds.

6 FUTURE MANAGEMENT AND GOVERNANCE

ToR 5: Report on options for future management and governance with particular attention to mechanisms (project oversight, project management, and technical advice) that will maximise the prospects of integration of CABLE with other initiatives, including ACCESS, hydrology modelling etc and realise national and international level outcomes.

CABLE's evolution as a community model will be shaped by the evolving science and operational priorities of its stakeholders. These are not entirely predictable and are likely to change over time. A management environment that can maximise the utility of advances made by any of CABLE's users is therefore key, both for the efficient use of research resources and for engaging the community's interest and ownership over CABLE's development. To achieve such an environment, the management of CABLE as a community model requires the following:

1. A governance structure that promotes a shared vision and ownership of model development directions and provides clear mechanisms for the adoption of new model developments in the core model.
2. Clear version control of model code and coding standards. Benchmarking of successive versions of the model and comprehensive documentation.
3. A range of communication options to allow interaction between all CABLE users
4. User support and training

Each is addressed in turn below.

6.1 Governance structures

We recommend the formation of a CABLE *management committee*, along with a *technical support group* and the appointment of a *CABLE coordinator* to facilitate the operation of the committee and communication with CABLE users. We also recognise value in the CABLE management committee reporting to and seeking advice from a body representing CABLE's stakeholders i.e. CAWCR and the universities. We considered recommending a CABLE oversight committee but have concluded that this is not necessary. Rather, we recommend that CABLE become a standing agenda item on a high-level committee or body that provides oversight for a number of CAWCR-university activities. Such a committee would sit between individual activities (e.g. CABLE) and the DCCEE High level coordination group.

Recommendation 6: That CABLE management structure consist of (1) a CABLE management committee; (2) a technical support group and (3) a CABLE coordinator.

The roles and responsibilities of the *management committee* would be:

a) To provide broad science directions for CABLE subject to the needs of stakeholders.
b) Maintain a record of who is working on different areas of the CABLE code, aid communication between parties interested in similar types of research and facilitate the creation of working groups as required.

c) Devise and review benchmarking tests for any proposed changes to the CABLE repository trunk and initiate extra tests where required.
d) Review documentation of any proposed changes to the CABLE repository trunk and integrate these into existing documentation if proposed changes are approved.
e) Identify potential conflicts (either structural or scientific) in multiple CABLE development proposals.
f) Request or perform (where resourced) ACCESS-CM tests of proposed changes if required.
g) Approve changes to CABLE trunk and determine trunk versions to be released as official updates of CABLE.
h) Recognise and document successful developments/approved changes, possibly through a CABLE annual report.

The CABLE management committee would need to meet at least every second month. It would be chaired by the CABLE coordinator and include representatives of each major group involved in CABLE development and one member of the technical support group. Members of the group need to have a good knowledge of the CABLE code. An interim CABLE management group has been formed and has been operating for approximately 12 months.

The roles and responsibilities of the *technical support group* would be:

a) Management of the CABLE code repository including tagging repository trunk versions when official releases are approved.
b) Updating CABLE libraries for different coupled models for official CABLE releases, and mirroring these releases on the existing CABLE Sharepoint site.
c) Providing user support and training in technical aspects of using CABLE.
d) Providing a CABLE email help facility and responding to enquiries (initially as part of the ACCESS help facility).
e) Setting up code verification test runs for CABLE (offline and for key atmospheric models).
f) Assisting with aspects of the CABLE benchmarking process, including:
    a. Checking coding standards are met in any new code.
    b. Aid in the development of standardised offline and coupled (atmosphere-land model) evaluation tests for benchmarking, including the collation and formatting of input/forcing datasets.
    c. Help deliver atmosphere-ocean coupled model runs (ACCESS) for benchmarking purposes

The technical support group should include all staff who are regularly involved in providing technical support to CABLE (currently 1 CSIRO, 2 CoECSS) but may also involve those with a wider (ACCESS) role.

The roles and responsibilities of the *CABLE coordinator* would be:

a) Ensuring reporting needs on CABLE are met
b) Organise and chair meetings of the management committee, distribute agenda and action items.

c) Liaise with technical support group to ensure CABLE user needs are being met
d) Facilitate communication between CABLE users through a CABLE email list or other media, and annual (or 6 monthly) meetings
e) Facilitate community-wide science development through working groups
f) Provide mechanisms for CABLE achievements to be promoted e.g. web-site, possible annual report

Rachel Law (CSIRO) has been acting in this role for approximately 12 months with a commitment of ~0.2 EFT (excluding writing this document). It is likely that the role will develop substantially over the next few years, requiring an increased time commitment of ~0.5 EFT and requiring some support in the communication aspects of the role.

6.2 Benchmarking, software engineering, and model code

The ability of this management structure to translate individual scientific modelling advances to community-wide benefits hinges on the efficiency and effectiveness of the benchmarking process. To continue to engage the broader CABLE developer community it has be perceived as fair and impartial. Developing appropriate standardised tests across the range of CABLE's output variables, collating the data sets and building the benchmarking infrastructure requires considerable resourcing. It requires both scientific and technical expertise to deliver and maintain.

CABLE runs as a standalone land surface model with prescribed meteorological forcing ('offline') or coupled to a number of different atmospheric models. As such it is important to distinguish between core science code which aims to be common across all model configurations, and interface code which is used for coupling or to manage the input-output needs of the offline version.

We recommend that all CABLE code (science and interface routines) be kept in an Apache subversion (svn) repository at NCI (https://trac.nci.org.au/svn/cable/) and all development work on this code will occur within this repository. The repository needs to be easily accessible to both CAWCR and university users and hence is best hosted on a NCI machine. A repository meeting these requirements has been set up and is being populated with code that is applicable to offline, ACCESS and Mk3L applications. CABLE code can then be compiled as a library with subsequent linking to a given atmospheric model. Other CABLE model versions will be added to the repository when they are made compatible with CABLE's core science routines.

Recommendation 7: That the parties involved in the development of CABLE allocate resources to building the relationships and structures needed for effective community model development, including (a) version control and file sharing (using Apache subversion on a NCI machine), (b) standardised benchmarking procedures, (c) a dynamic website to facilitate communication, and (d) regular meetings.

An official release of CABLE v2.0 is anticipated by 30/06/12. This will form the initial 'trunk' version of the repository. Changing or adding code to the trunk requires compliance with a procedure being defined by the CABLE *management committee*. The procedure will involve a series of benchmarking tests (single-site offline, global offline, atmosphere only, full ACCESS model) to document the impact of any change. Incorporation of a change into the trunk will depend on the nature of the change and the impact on model behaviour. A draft procedure has been documented and will be updated as model development occurs and the benchmarking process is refined.

6.3 Licensing

As noted in Sec 4.3, CABLE code is currently made available for research and non-commercial applications through the use of the 'CABLE' Academic User Licence Agreement (Appendix 4). By using the CABLE software, users are assumed to have read the licence. There is no requirement to sign the licence agreement, but users are required to apply to use CABLE (a registration form is provided) and this gives them a username and password for the CABLE sharepoint site (see Sec 6.4.b) where the code is currently available. The licence permits users to make improvements to the code which they own, but requires users to disclose these improvements to CSIRO on request, and to grant CSIRO with a 'non-exclusive, worldwide, royalty-free, perpetual, irrevocable licence (including a right of sub-licence) to use, adapt and exploit your Improvements for any purpose.' The clause that grants users ownership of their improvements means that current CABLE code (v1.4b and v2.0) already has parts which would not be CSIRO owned.

With CABLE's transition to a community model, and new mechanisms for CABLE's code distribution (through a NCI machine), we recommend that CABLE's current licence be revised or that CABLE be distributed under some form of Open Source agreement. In particular we recommend that CSIRO is, in future, seen as *custodian* of the CABLE code rather than *owner* of the code. We see value in continuing to require CABLE users to register. This allows CABLE developments to be communicated to users, and provides a measure of how widely CABLE is being used.

Recommendation 8: That CSIRO and CoECSS jointly explore licencing arrangements for CABLE IP that are consistent with the nature of CABLE as a community model, initially by evaluating the current licence.
Recommendation 9: That CSIRO be the agreed primary custodian of CABLE, and that CAWCR Management agree on an appropriate point of accountability within CSIRO and BoM for CABLE management and interactions with CoECSS and other partners.

Any revision or new form of CABLE licence also needs to consider the relationship of CABLE to the atmospheric models it is coupled to. These range from those with very restricted usage agreements (e.g. the UM) to those which are very open (e.g. WRF). Inclusion of CABLE in the Met Office's version of the UM might give ownership of CABLE to the Met Office (under CSIRO's current agreement with UKMO), while inclusion of CABLE in WRF would require a licence that allows free distribution of CABLE code. We also note that a version of CABLE is currently distributed as part of CCAM without CCAM users being required to sign the current CABLE licence.

Since the current and proposed future licence for CABLE does not include commercial use of CABLE, separate arrangements would be needed if commercial applications were envisaged. As custodian of CABLE, CSIRO would need to lead the negotiation of appropriate arrangements with those proposing commercial work, on behalf of the CABLE community.

6.4 Communication

With CABLE users and developers across Australia (and internationally) effective means of communication are vital. Areas that require continued/further development include:

- A CABLE website. CABLE currently has a small web presence on both the ACCESS and CAWCR web-sites (http://www.accessimulator.org.au/cable/, http://www.cawcr.gov.au/projects/access/cable/), providing CABLE documentation, registration information and a link to the CABLE sharepoint site (https://teams.csiro.au/sites/cable/default.aspx). An increased web presence would be desirable, show-casing CABLE projects and allowing CABLE users to interact with each other. Preliminary work is required to determine the desired scope of a CABLE website, where that website is best hosted to meet the desired scope and how the web-site would be managed, maintained and resourced (see Recommendation 7 above). As a community model, CABLE needs a web-site that can be effectively used across the CABLE community.
- CABLE sharepoint site (https://teams.csiro.au/sites/cable/default.aspx). This is our current mechanism for distributing CABLE code, and also contains documentation, presentations, publication lists and limited CABLE news. It is not clear that CABLE users are making regular use of this site, perhaps because site updates have occurred in an ad-hoc manner, and due to password expiry issues for non-CSIRO staff. The ongoing use of this site needs to be clarified amongst the CABLE community, although it may have a continued role in the provision of official releases of the CABLE code for those (e.g. from overseas) who may not have access to a NCI account and consequently the CABLE code repository.
- CABLE email list (https://lists.csiro.au/mailman/listinfo/cable-users): This list was set up in April 2011 and provides a forum for CABLE users to exchange news. Email traffic has been relatively limited but monthly CABLE news updates are being compiled and distributed by the CABLE coordinator.
- CABLE Trac site (https://trac.nci.org.au/trac/cable/): As part of the CABLE subversion repository implementation at NCI, a CABLE trac site is also established. This is designed to aid communication between CABLE developers and includes a wiki, a ‘ticketing’ system for logging code developments and a web interface for browsing the code repository. Guidelines are currently being prepared to make most effective use of this system.
- Workshops. It is recommended that CABLE workshops occur at least annually and preferably six-monthly rotating between Melbourne, Sydney and Canberra. Regular workshops would require travel funding or reliable video-conferencing facilities (Aspendale lecture theatre facilities seem too often have problems). The CoECSS is able to contribute resources to these workshops. (See Recommendation 7, Section 6.2).

6.5 User support and training

CABLE v2.0 needs to be released with updated model documentation and a current user manual. Users can also be supported through the provision of example simulations with expected output (code verification tests). While some of this work will be the responsibility of the technical support group, significant input may be required from those people most familiar with key components of the CABLE code.

A training program for new users could be developed and resourced through the CoECSS. The CoECSS is also able to resource travel that supports CABLE development, either for CABLE developers to work with overseas groups to bring new skills/capacity to CABLE, or to bring overseas researchers to Australia to work with CABLE.

7 RISKS OF NOT PROCEEDING WITH CABLE

The risks of not proceeding with CABLE can be analysed in terms of potential threats to the six major societal and policy drivers identified in Section 2.1.

(1) *Weather forecasting*: The current Unified Model (UM) uses JULES as its land surface scheme, with plans to transition to CABLE as a suitable coupler is developed (Recommendation 2). In Section 2.1.1 we identified three drivers for this transition: Australian NWP should use a land surface model (CABLE) that recognises key differences between Australian and typical northern hemisphere biomes; use of CABLE makes available to the NWP a rigorously tested land surface scheme for Australian biomes; and use of CABLE ensures consistency of land surface modelling between NWP, climate and other arenas that depend on weather and climate forecasts, including water, carbon and environmental information and management, and integrated assessment. The risk of not proceeding with CABLE is precisely the converse of these benefits.

(2) *Climate change projections:* CABLE is already used in the climate version of the UM and is therefore integral to the Australian climate projections for IPCC AR5. The crucial benefit brought by CABLE is that unlike many other land surface schemes, including JULES, it incorporates all of water, carbon and nutrient dynamics (through the coupling between CABLE and CASA-CNP), so climate projections with CABLE can explore critical potential feedbacks such as the carbon-nutrient feedback – essentially that the terrestrial CO_2 sink may become N and P limited in future, exacerbating climate change. Not proceeding with CABLE would close off exploration of these critical feedbacks.

(3) *Water resources management:* There is already a well-recognised need in the Australian community to establish consistency between the land-surface scheme in NWP and climate models (CABLE) and hydrological models used in water resources management (mainly AWRA); see Section 2.1.3 and Recommendation 3. Not proceeding with CABLE would set back the efforts to bring about this consistency, by several years.

(4) *Carbon management and accounting:* Through the REgional Carbon Cycle Assessment and Processes (RECCAP) project, CABLE is already making key contributions to full carbon accounting for Australia (Section 3.1.2). These contributions would be nullified by a decision not to proceed with CABLE.

(5) *Environmental information and accounting:* An important potential development is the interest by many Government agencies in environmental and "triple-bottom-line" accounting (Section 2.1.5). CABLE is the primary means by which CAWCR can contribute in this domain, and a decision not to proceed would close off an entire potential area of application.

(6) *Integrated assessment:* In this domain, CABLE is the primary tool by which CAWCR can contribute high-level process knowledge of critical terrestrial interactions. A decision not to proceed would close off an entire potential area of application for CAWCR.

There are further risks associated with a decision not to proceed with CABLE, many of which are associated with its nature as a community model. Continuing the numbering:

(7) There are only a small number of LSMs designed for weather and climate research that are maintained, documented and accessible. Well known models like CLM, ORCHIDEE, SiB2, JULES are each independent LSMs that represent the same processes as CABLE. CABLE is currently competitive with any other LSM and provides an independent sample in the "space" that is land modelling. In this sense, there is an international-scale risk to not proceeding with CABLE as this reduces the sample size of land models that couple the energy, water and carbon fluxes at the canopy-level by one model, or 10-15%.

(8) CABLE provides a catalyst to Australian land-surface science. Australian research can be integrated through CABLE, to unite hydrology, soil science, land cover change, phenology, ecophysiology, palaeoclimate etc. All can invest in capacity building through CABLE. Without CABLE, this science will diffuse, and will contribute *ad hoc* to other land surface models such as JULES, ORCHIDEE, CLM.

(9) CABLE provides us flexibility to couple land surface modelling to other modelling systems of our choice. We can collaborate independent of the Hadley Centre with groups building CASA-CNP, the Land Information System, WRF etc. This provides a capacity to choose tools of choice for the challenge at hand – something we might not be able to do if we used another model under licence.

(10) Australia has scientific priorities that are different from overseas groups: semi-arid conditions, the importance of soil evaporation, ground water interactions, deeply-rooted vegetation, the diversity of landscapes in Australia ranging from the tropics to sub-alpine, the significant role of nutrient limitation; all provide the need for a land surface model tailored to our specific science need.

(11) CABLE contains Australian-specific science configured for Australian climatic conditions. Modes of variability drive long-time scale variability in Australia that affects Australian terrestrial processes. These are unlikely to be resolved in (for example) JULES since this model was built using seasonally-defined mid-latitude data.

(12) CABLE acts as a vehicle for the integration of the Australian research community into the international science arena, in the areas of the effects of land surfaces on weather, climate, and the carbon and water cycle.

(13) There has been a significant investment in CABLE. Failing to proceed with development of the model is likely to be viewed negatively by funders and risk investment in other components.

(14) CABLE has a very broad community of users – this places a level of demand on the model that requires local expertise to be developed and maintained. Importing a model that is software engineered for a different range or breadth of users risks disenfranchising Australian-based users.

(15) There is always a risk, at some point in the future, whatever model we choose to import to replace CABLE will cease to be available to us.

For all of these reasons, a decision not to proceed with CABLE would inevitably have serious repercussions: for the affected organisations; for the researchers involved; for Australia's national interests; for the quality of science in general; and for the global community's ability to direct itself towards a sustainable future.

APPENDIX 1: GLOSSARY

ACCESS	Australia Community Climate and Earth System Simulator
ACCESS1.3	Version of ACCESS with CABLE submitted to CMIP5
AGO	Australian Greenhouse Office
ALOA	Atmosphere and Land Observation and Assessment program (CSIRO)
AMIP	Atmospheric Model Intercomparison Project (also used to denote an atmosphere only climate model simulation using prescribed sea surface temperatures)
AR5	Assessment Report 5 of the Intergovernmental Panel on Climate Change
AusCover	Australian biophysical map products and remote sensing data time-series
AWAP	Australian Water Availability Project
AWRA	Australian Water Resources Assessment
AWRA-G	Australian Water Resources Assessment – groundwater
AWRA-L	Australian Water Resources Assessment – land
AWRA-R	Australian Water Resources Assessment – river
BenchANN	Statistical benchmark using artificial neural network [Fig 2]
BenchMLR	Statistical benchmark using multiple linear regression [Fig 2]
BIOS2	High-resolution (5 km) framework for off-line modelling of coupled carbon, water, energy and nutrient (N and P) cycles
BoM	Bureau of Meteorology (Australia)
Budyko	Based on Budyko (1956) and assumes precipitation equals surface evaporation and run-off on decadal timescales
BVOC	biogenic volatile organic compounds
C	carbon
CABLE	Community Atmosphere Biosphere Land Exchange
CASA	Carnegie-Ames-Stanford Approach
CASA-CNP	Carnegie-Ames-Stanford Approach with Carbon, Nitrogen, Phosphorus (carbon and nutrient pool model)
CAWCR	Centre for Australian Weather and Climate Research
CBM	CSIRO Biosphere Model
CCAM	CSIRO Conformal-cubic Atmospheric Model
CH_4	methane
C-LAMP	Carbon-Land Model Intercomparison Project
CLM	Community Land Model (National Center for Atmospheric Research, USA)
CLW	CSIRO Land and Water
CM	Coupled Model
CMAR	CSIRO Marine and Atmospheric Research
CMIP3	Coupled Model Intercomparison Project 3
CMIP5	Coupled Model Intercomparison Project 5
CN	Carbon and Nitrogen
CNP	Carbon, Nitrogen and Phosphorus
COAG	Council of Australian Governments
CoECSS	Centre of Excellence for Climate System Science
CO_2	Carbon dioxide
CO2CRC	Carbon dioxide Cooperative Research Centre
CSCS	CSIRO soil-canopy scheme
CSIR	Council for Scientific and Industrial Research (South Africa)

CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
C4MIP	Coupled climate-carbon cycle model intercomparison project
DA	Data assimilation
DCCEE	Department of Climate Change and Energy Efficiency
DFAT	Department of Foreign Affairs and Trade (Australia)
EFT	Equivalent Full-time staff
eMAST	Ecosystem Modelling and Scaling Infrastructure
ERAi	ERA-Interim [fig 6]
ESM	Earth System Modelling program (CSIRO)
EPS	ensemble prediction systems
ET	Evapotranspiration
FACE	Free Air CO_2 Experiment
FluxNet	a global network of micrometeorological tower sites
GIAM	Global Integrated Assessment Modelling
GCM	General Circulation Model
GEWEX	Global Energy and Water Cycle Experiment
GHG	Greenhouse gas
GLACE	Global Land-Atmosphere Coupling Experiment
GLASS	Global Land/Atmosphere System Study
GPCC	Global Precipitation Climatology Centre
GPP	Gross Primary Productivity
GSWP2	Global Soil Wetness Project
HDO	Water, with one deuterium atom
$H_2{}^{18}O$	Water, isotope 18
IAM	Integrated Assessment Modelling
ICP	Integrated Carbon Pathways (CSIRO)
IGBP	International Geosphere-Biosphere Programme
ILAMB	International Land Model Benchmarking
IOCI	Indian Ocean Climate Initiative
IP	Intellectual property
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Assessment Report 5
ISLSCP II	International Satellite Land-Surface Climatology Project
JULES	Joint UK Land Environment Simulator
KP	Kyoto Protocol
LAI	Leaf Area Index
LIS	Land Information System
LoCo	Local coupled land-atmospheric modelling
LSM	Land surface model
LUCID	Land Use, IDentification of robust impacts
LULCC	land use and land cover change
Mk3L	CSIRO Mark 3 climate model, Low resolution
MOSES	Met Office Surface Exchange System (UK)
N	Nitrogen
NBP	Net biosphere production of carbon
NCAR	National Center for Atmospheric Research (USA)
NCAS	National Carbon Accounting System
NCI	National Computing Infrastructure
NEE	net ecosystem exchange of carbon
NGGI	National Greenhouse Gas Inventory
NIAM	National Integrated Assessment Modelling

NPP	Net Primary Productivity
NWP	Numerical Weather Prediction
N_2O	nitrous oxide
OCE	Office of the Chief Executive (CSIRO)
ORCHIDEE	Organizing Carbon and Hydrology in Dynamic EcosystEms (French global land surface model)
OzFlux	A national ecosystem/ atmosphere research network
P	Phosphorus
PALS	Protocol for Analysis of Land Surface models
PBL	planetary boundary layer
PMSEIC	The Prime Minister's Science, Engineering and Innovation Council
PPM	Parts per million [Fig 4]
R&D	Research and Development
RECCAP	REgional Carbon Cycle Assessment and Processes
SCAM	Soil Canopy Atmosphere Model
SEACI	South East Australian Climate Initiative
SiB	Simple Biosphere Model
SLI	soil-litter-iso
TAPM	The Air Pollution Model
TERN	Terrestrial Ecosystem Research Network
ToR	Terms of Reference
UK	United Kingdom
UKMO	UK Met Office
UM	Unified Model (Met Office)
USA	United States of America
WIRADA	Water Information Research and Development Alliance
WRF	Weather Research and Forecasting model

APPENDIX 2: LIST OF CABLE USERS

CSIRO:
Marine and Atmospheric Research (24)
Land and Water (6)
Ecosystem Sciences (4)
Plant Industry (1)

Bureau of Meteorology (5)

Australian Universities:
Australian National University (2)
Flinders University (1)
Macquarie University (1)
Monash University (7)
Murdoch University (2)
Sydney University (1)
University of Melbourne (8)
University of Queensland (1)
University of Newcastle (1)
University of New South Wales (12)
University of Technology Sydney (7)

Other Australian institutions:
ANSTO (1)
QDPI (2)

Overseas
Brazil (3)
China, Chinese Academy of Sciences (6)
China, Beijing Academy of Agriculture and Forestry Sciences (2)
China, Institute of cold and arid regions (1)
China, Nanjing University of information technology and meteorology (1)
China, Beijing Normal University (2)
France, Institute of alpine ecology (1)
Indonesia (1)
Israel (1)
Spain, University Madrid (1)
South Africa, CSIR (1)
Taiwan (1)
Switzerland, Met service (1)
UK, Met Office (1)
UK, King's college London (1)
UK, University of Reading (1)
USA, University of Oklahoma (2)
USA, NASA JPL (1)

APPENDIX 3: CABLE PUBLICATION LIST

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APPENDIX 5: COUPLING OF CABLE TO THE UM: ISSUES

Introduction

The land surface scheme in the Unified Model has, until recently, been the Met Office Surface Exchange System (MOSES). This is fully integrated in the UM code. From UM7.6, the Joint UK Land Environment Simulator (JULES) has also been implemented in the UM. JULES is designed to run in stand-alone mode, as well as coupled to the UM. When implemented in the UM, JULES can be run in a 'scientifically neutral' configuration relative to MOSES although new science is also available in JULES. The scientific core of JULES uses the same or similar subroutines as MOSES. The calling paths for JULES within the UM are very similar to that for MOSES, but the code itself is located within src/land directories within the UM repository (up to UM8.0) and in a separate JULES repository from UM8.1. By moving JULES into a separate repository, the development path for JULES is separated from the development path for the UM.

CABLE is currently coupled to UM7.3 (further details below). Future coupling of CABLE to the UM, needs to account for the move from MOSES to JULES. Hence there has been a stated need to 'couple CABLE to the UM via JULES' but little clarity about what is meant by this. This document aims to define this task.
The drivers for reassessing how CABLE is coupled to the UM are:

a) Easier/faster coupling to future UM versions. Coupling CABLE to UM7.3 has been very time-consuming, in part due to unfamiliarity with the UM code, and in part due to structural issues within the UM code which did not easily accommodate CABLE.

b) Data assimilation needs. By closely aligning the CABLE and JULES interfaces with the UM, it is easier to set up assimilation of land surface fields (e.g. soil temperature and moisture) into either land surface scheme. In particular the data assimilation technique being used requires offline simulations of CABLE or JULES. While CABLE can already run offline using its own forcing fields etc, coupling CABLE to offline-JULES would allow CABLE to run with forcing fields etc prepared for JULES and reduce data pre-processing overheads.

c) Scientific comparison of different parts of CABLE/JULES. Increased modularity of both CABLE and JULES, would allow different components of the land surface schemes to be compared. An early priority might be to separate out the modeling of non-vegetated surfaces e.g. urban tiles.

It is worth noting that coupling to meet the requirements of drivers (a) and (b) could likely be achieved more easily and quickly than meeting the requirements of driver (c), which would likely require more extensive code modification. Consequently there needs to be agreement on what priority is given to each driver.

Coupling of CABLE to v7.3

A version of CABLE, based on v1.4b, has been coupled directly to the UM and has been included in ACCESS 1.3 coupled model simulations. Preliminary evaluation of the

simulations suggests that CABLE is performing satisfactorily. CABLE coupling was directly into the UM7.3 and required code changes in many UM subroutines.
A pre-release version of CABLE2.0 has also been coupled to the UM. Major changes from CABLE1.4b include updated CABLE science routines to be comparable across offline, ACCESS and Mk3L versions, inclusion of CASA-CNP and cleaner interface code with the UM. CABLE remains directly coupled into the UM 7.3. Testing of this version is ongoing.
The code changes made to implement this coupling can be summarized as follows:

- Calls to CABLE routines. CABLE science routines are consolidated under four cable drivers. Each driver is called from a different subroutine in the UM code, corresponding to points where the UM either has available or is ready to receive, particular land-surface variables. In the JULES implementation, three of these subroutines would lie within JULES code, one would be in UM code. Specifically the four calls to CABLE (*from UM 7.3*) are as follows

CALL cable_rad_driver	from	control/top_level/ glue_rad-rad_ctl2.F90
CALL cable_explicit_driver	from	atmosphere/boundary_layer/sf_exch.F90
CALL cable_implicit_driver	from	atmosphere/boundary_layer/sf_impl.F90
CALL cable_hyd_driver	from	atmosphere/land_surface/hydrol.F90

  The first effective and also main call to CABLE (*cable_explicit_driver*) is from the subroutine sf_exch. Memory for persistent CABLE variables is allocated in *cable_explicit_driver* subroutines, and initialized from the corresponding, passed UM variables. In general, the UM uses multi-dimensional arrays to store these variables, in which not all elements represent active land points in the model. CABLE, on the other hand, is designed to process a one dimensional vector, in which all elements are expected to be active land points. Therefore, the variables passed from the UM are *re-packed* for use within CABLE. In addition, some of the passed UM variables are altered (e.g. change of units) to be consistent with CABLE usage. On this *explicit* call to CABLE, all elements of the CABLE model are executed except *soilsnow* and carbon routines. Finally, variables are unpacked and reformatted for passing back to the UM.
  The *implicit* call to CABLE (*cable_implicit_driver*) further updates some meteorological forcing (including rain and snow precipitation) before calling the previously omitted *soilsnow* and carbon routines.

  The *hydrology* call to CABLE (*cable_hyd_driver*) simply unpacks variables calculated in the *implicit* call at the appropriate place in the UM.

  The first call to CABLE (*cable_rad_driver*) encountered in the UM is actually from glue_rad-rad_ctl2.F90, and remains in the UM code following the JULES implementation. However, this is conditionally avoided on the first timestep, with the necessary fields obtained from the start dump. Thereafter, *cable_rad_driver* essentially updates surface albedos for the UM. This may be reversed in the future, so that *cable_rad_driver* is called on every radiation timestep (not necessarily equal to atmospheric timestep). Whilst being a relatively straight forward exercise, this is a non-trivial task as all necessary memory allocation and initializations need to be migrated to *cable_explicit_driver*.

- Addition of a logical switch for CABLE (l_cable). As well as switching on the calls to CABLE drivers this switch defines parts of the MOSES code that are still required even when running CABLE and which parts of MOSES can be omitted. Maintenance of some MOSES code is required because MOSES simulates grid-cell fluxes for sea-ice as well as land. These sea-ice grid-cells are not included in CABLE and hence have to be picked up from MOSES. It is likely that this implementation runs MOSES code for grid-cells that are then overwritten by CABLE calculations and efficiencies may be gained by avoiding this in future.

- MOSES is set up to run with five vegetation types and four non-vegetated types. While the UM code defines parameters such as 'nveg' and 'npft', the limit of nine surface types was found to be hard-wired in many places within the UM code. CABLE typically uses more vegetation types than MOSES, necessitating many small changes to UM subroutines. It is understood that this limitation on number of vegetation types will be removed from UM8.2 onwards (but UKCA code may still assume 9 surface types).
- CABLE also runs with a different number of soil levels (6) than MOSES (4). Again this was found to be hard-wired within the UM7.3 code but may now have been generalised. Additionally, CABLE maintains separate soil variables for each of the surface types within a grid-cell (tiled soil) while MOSES does not. Consequently variables such as soil temperature and soil moisture become 5 dimensional in CABLE (longitude, latitude, soil level, surface type, time). The input/output routines of the UM do not currently support 5 dimensional arrays. To work around this, each soil variable at each soil level is defined as a separate prognostic variable within the UM. This solution works satisfactorily but is not very elegant.
- CABLE makes use of the input/output (STASH) code provided in the UM. In many cases CABLE was able to make use of STASH variables that had already been defined for MOSES. Additional prognostic and diagnostic variables were also required, particularly when including the CASA-CNP biogeochemistry module. To make room for these extra variables, STASH was extended to allow for STASH codes greater than 512. In our current implementation extra CABLE/CASA-CNP variables have been allocated 800+ numbers. Some code changes are required for each new variable, as well as changes in the set-up of the model simulations (through the STASHMASTER file).
- The UM calculates radiation three hourly. This caused some problems because the UM was not seeing changes in albedo calculated every timestep in CABLE. Consequently some simplification of the snow albedo calculation in CABLE was required.

Other than the calls to CABLE from the UM, there are a total of ~40 files which have been modified in some way, mostly to deal with these UM structural issues. The most significant changes are those mentioned above to support CABLE variables in STASH with increased number of vegetation types and soil layers. Other changes involve the logical switch for CABLE (l_cable) used in conditional blocks. Finally there are several files which contain no change other than that to argument lists as variables are passed through to CABLE.

For the coupling of CABLEv1.4b to ACCESS, CABLE code resides in the UM repository under src/atmosphere/CABLE. For the CABLEv2.0 coupling to ACCESS, CABLE code has been moved into a separate CABLE repository. This code can be compiled as a library and linked to the main UM compile.

While not directly related to the implementation of CABLE, there has also been significant coding work done on UM7.3 to provide more flexibility on the input of trace gas surface fluxes to the passive tracer transport scheme in the code, to implement a CO_2 and trace gas mass fixer and to provide some parameterized chemistry for a CH_4 transport comparison coordinated by the TransCom group. These changes are documented in Corbin and Law (2011).

Future coupling of CABLE to JULES and the UM

A sensible first step appears to be to couple CABLE into stand-alone JULES code. This is desirable for data assimilation work and offline evaluation, but should then facilitate coupling into the UM by highlighting remaining structural differences between JULES and CABLE code. By bringing all of the CABLE drivers into stand-alone JULES, we should be able to minimize the changes/additions required for CABLE in the UM (rather than JULES) repository.

From a quick look at the implementation of JULES in UM8.0, and discussions with M. Hendry (Met Office) on developments after UM8.0, the following issues will need to be considered for future coupling:

- UM8.2 or later is required to allow for a flexible number of surface types. It is our understanding that a flexible number of soil layers has also been implemented recently.
- Soil tiling is implemented in CABLE but, to our knowledge, is only under discussion for implementation in JULES. Discussions with Met Office staff would be helpful to determine how soil variables are best implemented to allow for soil tiling (5 dimensional arrays).
- The radiation driver call for CABLE needs to be moved out of the UM and into JULES. There is a call to the JULES subroutine tile_albedo at the point where the radiation driver is currently called, so perhaps the radiation driver can be moved into this subroutine (since it has similar functionality – to calculate surface albedos for CABLE).
- The calculation of fluxes for sea-ice points needs to be reconsidered. We need to be clear about how much of the JULES code we need to maintain for this calculation, in both atmosphere-only and coupled model applications. In cases where some JULES code is required, we should consider whether this is best done by conditional blocks of code (If L_CABLE then ….) or whether parallel subroutines would be more appropriate e.g. a sf_exch.f90 and a sf_exch_cable.f90
- Allocation of STASH variables might benefit from more coordination with Met Office staff. Clarity over which JULES variables are 'co-opted' by CABLE, and which stash numbers can be used for new variables would be helpful.
- Maintenance of some of the tracer enhancements made to UM7.3 would be desirable for climate applications but is unlikely to be necessary for NWP. These code changes are more likely to reside in the UM repository than the JULES one.

Development of a new coupling strategy should aim to identify the minimum set of changes that we require in JULES and/or the UM that would provide ‘plug-in’ points for CABLE and could become part of an official UM release. Under this scenario, CABLE development would continue along its own path in the CABLE repository. This allows CABLE to remain autonomous, but may not be ideal for driver (c) above, for which substantial code restructure is likely required to interchange/compare process parameterisations.

It has been proposed that Matt Pryor (Met Office) visit CAWCR in late 2012. Since he is responsible for the JULES stand-alone code, this visit would greatly benefit the coupling effort. Longer term directions for coupling either JULES or CABLE to the UM could also be discussed, in particular whether there is value to moving to a formal land surface model coupler.

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