Hydrol. Earth Syst. Sci. Discuss., 12, 10789–10825, 2015
www.hydrol-earth-syst-sci-discuss.net/12/10789/2015/
doi:10.5194/hessd-12-10789-2015

Hydrology and Earth System Sciences
Open Access
Discussions

Modelling evapotranspiration during precipitation deficits: identifying critical processes in a land surface model

A. M. Ukkola[1], A. J. Pitman[1,2], M. Decker[1,2], M. G. De Kauwe[3], G. Abramowitz[1,2], J. Kala[1,4], and Y.-P. Wang[5]

[1]ARC Centre of Excellence for Climate System Science, University of New South Wales, Kensington, NSW 2052, Australia
[2]Climate Change Research Centre, University of New South Wales, Kensington, NSW 2052, Australia
[3]Department of Biological Sciences, Macquarie University, Balaclava Road, North Ryde, NSW 2109, Australia
[4]Murdoch University, School of Veterinary and Life Sciences, Environmental and Conservation Sciences, Murdoch, 6150, WA, Australia
[5]CSIRO Ocean and Atmosphere, Aspendale, Victoria, 3195, Australia

Received: 28 September 2015 – Accepted: 5 October 2015 – Published: 21 October 2015

Correspondence to: A. M. Ukkola (amukkola@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Surface fluxes from land surface models (LSM) have traditionally been evaluated against monthly, seasonal or annual mean states. The limited ability of LSMs to reproduce observed evaporative fluxes under water-stressed conditions has been previously noted, but very few studies have systematically evaluated these models during rainfall deficits. We evaluated latent heat flux simulated by the Community Atmosphere Biosphere Land Exchange (CABLE) LSM across 20 flux tower sites at sub-annual to inter-annual time scales, in particular focusing on model performance during seasonal-scale rainfall deficits. The importance of key model processes in capturing the latent heat flux are explored by employing alternative representations of hydrology, leaf area index, soil properties and stomatal conductance. We found that the representation of hydrological processes was critical for capturing observed declines in latent heat during rainfall deficits. By contrast, the effects of soil properties, LAI and stomatal conductance are shown to be highly site-specific. Whilst the standard model performs reasonably well at annual scales as measured by common metrics, it grossly underestimates latent heat during rainfall deficits. A new version of CABLE, with a more physically consistent representation of hydrology, captures the variation in the latent heat flux during seasonal-scale rainfall deficits better than earlier versions but remaining biases point to future research needs. Our results highlight the importance of evaluating LSMs under water-stressed conditions and across multiple plant functional types and climate regimes.

1 Introduction

Land surface models (LSMs) simulate the exchange of water and energy between the land surface and the atmosphere (Pitman, 2003). They control how net radiation is partitioned between sensible and latent heat (Q_E), and how rainfall is partitioned between evaporation and runoff and therefore form an integral part of global climate models.

LSMs have been extensively evaluated for simulated water, energy and carbon fluxes, typically at seasonal to inter-annual time scales (Abramowitz et al., 2007; Best et al., 2015; Blyth et al., 2011; Dirmeyer, 2011; Zhou et al., 2012). LSMs have been found to perform reasonably well under well-watered conditions (e.g. Best et al., 2015) but are less able to capture fluxes during water-stressed conditions (Li et al., 2012). Given the long history of systematic model evaluation (Best et al., 2015; Dirmeyer, 2011; Henderson-Sellers et al., 1995), it is remarkable that very few studies have systematically evaluated the ability of LSMs to simulate hydrological processes during precipitation or soil moisture deficits, although Powell et al. (2013) and Prudhomme et al. (2011) are some notable exceptions.

The ability to simulate a drying landscape is one of the pre-requisites for reliable projections of drought by a LSM and therefore by a climate model. Droughts are expected to increase in frequency and intensity (Allen et al., 2010; Trenberth et al., 2014) in some regions due to the effects of climate change (Collins et al., 2013). This would have profound implications for affected regions and their socio-economic systems. Unfortunately, there are large uncertainties in the evolution of historical (Dai, 2012) and future (Prudhomme et al., 2014) droughts. This is associated, in part, to differences in projected climate, particularly regional scale rainfall, or sparse observational records in the case of historical drought trends (Dai, 2011). However, there are also major weaknesses in the capability of the LSMs used in climate models to capture drought events. For example, Prudhomme et al. (2011) showed large differences between three global hydrological models in simulating historical hydrological droughts (i.e. streamflow deficits) in European catchments. The participating Joint UK Land Environment Simulator LSM (JULES; Best et al., 2011) was shown to overestimate both the duration and severity of droughts. Similarly, the projected occurrence of future droughts has been shown to be highly model dependent, with greater uncertainty in future projections arising from differences between hydrological models than from the climate model projections used to force them (Prudhomme et al., 2014).

HESSD
12, 10789–10825, 2015

We investigate the performance of the Australian Community Atmosphere–Biosphere Land Exchange (CABLE) in simulating observed declines in Q_E during rainfall deficits. We use Q_E because it is the variable that links the land surface energy, water and carbon budgets. It is also one of the variables supplied by the land surface to the atmosphere and is therefore important to a climate model. We do not use soil moisture as evaluating soil moisture from LSMs directly is problematic (Koster et al., 2009) due to different soil structures assumptions, storage capacity and timescales inherent in how LSMs represent this variable. There are also very few examples of full soil moisture profile observations with co-located meteorological forcing. By using Q_E, we can identify when this flux begins to become limited by soil moisture and then evaluate CABLE against these "dry-down" periods. This forms an important first step towards establishing the capability of CABLE to simulate drought events. This is particularly important because CABLE is the LSM used within the Australian Community Climate and Earth Systems Simulator (ACCESS; Bi et al., 2013), a global climate model which has participated in the 5th assessment report of the International Panel on Climate Change (IPCC, 2013) and is used for numerical weather prediction in Australia (Puri et al., 2013). If CABLE, or other LSMs, over- or underestimate the magnitude of Q_E at the onset of rainfall deficits, or drop too quickly or slowly during periods of low rainfall, they are also likely to fail to capture the magnitude and intensity of droughts.

We examine CABLE in the context of two key areas of uncertainty: how processes are parameterised and how associated parameters are selected. In terms of model parameterisations, we examine the hydrology and stomatal conductance modules. These have recently been revised and shown to improve seasonal to annual scale simulations of Q_E in CABLE (Decker, 2015; De Kauwe et al., 2015a). In terms of parameters, we quantify the uncertainty arising from soil texture and leaf area index (LAI) inputs. CABLE-simulated Q_E has been shown to be sensitive to these parameters but they remain uncertain at both site and large scales (Kala et al., 2014; Zhang et al., 2013). While other parameters, including other vegetation characteristics such as rooting depth (Li et al., 2012), are potentially important, soil texture and leaf area index can

HESSD
12, 10789–10825, 2015

be constrained from readily available global-scale datasets widely used in large-scale LSM applications.

We note it is possible to measure or calibrate some key parameters at site scales (Gupta et al., 1999; Leplastrier et al., 2002; Wang et al., 2001) to enable a LSM to better match an observed time series. This is not our goal; we are not trying to demonstrate how well CABLE can reproduce observed Q_E per se. Rather, we are examining where the model appears to fail for lack of process-level representation of a land surface component in ways that should be applicable to larger-scale applications of the model. While using calibration would improve a model's metrics, calibration is likely to lead to parameter values that perform well at the calibration site, but are likely to be over-fitted for broad scale application. Rather than using calibration, we utilise observed datasets that are similar or identical to those commonly used to run CABLE (and other LSMs) at regional to global scales. We examine whether variations in the LAI and soil properties, informed by the observations, enable our LSM to accurately capture the observations of Q_E. Where the LSM cannot capture the observations, despite variations in LAI and soil parameters, points to systematic errors in the model's representation of physical processes.

We therefore evaluate CABLE's simulation of Q_E across 20 globally distributed flux tower sites, covering a range of climates and vegetation types, with a specific focus on identifying key processes controlling model performance during rainfall deficits. While our analysis is restricted to site scales, flux tower measurements are direct observations of latent heat (Wang and Dickinson, 2012) and offer a valuable reference for model performance.

HESSD
12, 10789–10825, 2015

2 Methods

2.1 Flux tower sites

We evaluate CABLE performance against eddy covariance measurements across 20 flux tower sites globally (Fig. 1 and Table S1). The data were collated as part of the Protocol for the Analysis of Land Surface models (PALS; Abramowitz, 2012) Land sUrface Model Benchmarking Evaluation pRoject (PLUMBER; Best et al., 2015), originally obtained through the Fluxnet LaThuile Free Fair-Use subset (fluxnet.ornl.gov). The PLUMBER sites were chosen to represent a broad range of vegetation and climate types, whilst also maximising the length of measurement records (Best et al., 2015). Here, we focus on the results for six sites with a pronounced period of low precipitation, each representing a different climate and vegetation type, but provide results for all study sites as Supplement (Figs. S1–S4).

The 20 flux tower sites provide meteorological and flux measurements at 30 min time steps. The observed meteorological data (precipitation, short- and long-wave radiation, surface air pressure, air temperature, specific humidity and wind speed) were used to drive CABLE simulations. Observed Q_E was used to evaluate simulations.

2.2 Description of the CABLE LSM and model parameterisations

2.2.1 General description

The Community Atmosphere–Biosphere Land Exchange (CABLE) model is a LSM used to simulate energy, water and carbon fluxes and the partitioning of net radiation into latent and sensible heat fluxes. It can be employed offline with prescribed meteorology or within the Australian Community Climate Earth System Simulator coupled climate model (ACCESS; Bi et al., 2013). It has been used widely in coupled (Cruz et al., 2010; Lorenz and Pitman, 2014) and offline (Haverd et al., 2013; Huang et al., 2015; Zhou et al., 2012) simulations and has been extensively evaluated against flux site (De Kauwe et al., 2015c; Li et al., 2012; Wang et al., 2011; Williams et al., 2009) and regional to global-scale observations (Decker, 2015; De Kauwe et al., 2015a). Previous model inter-comparisons have shown that simulated latent and sensible heat fluxes perform comparably to other LSMs (Best et al., 2015).

CABLE consists of sub-models for radiation, canopy, soil and ecosystem carbon. Canopy processes are represented with a two-leaf model, which calculates photosynthesis, stomatal conductance and leaf temperature separately for sunlit and shaded leaves (Leuning, 1995; Wang and Leuning, 1998). The soil module simulates the transfer of heat and water within the soil and snowpack following the Richards equation. CABLE has 11 plant functional types (PFT). A detailed description of model components can be found in Wang et al. (2011).

We ran CABLE version 2.0 forced with site-specific meteorological data at 30 min time steps. Site PFT was determined by matching site vegetation (fluxnet.ornl.gov) to CABLE PFTs. PFT parameters were taken from a standard look-up table provided with CABLE 2.0 and were not calibrated to match site characteristics. The model was run using two alternative hydrological modules, two stomatal conductance parameterisations, three soil types and three LAI time series. The new hydrological scheme implements a topographic slope parameter, which was varied between two values in additional simulations. CABLE was run with all parameterisation combinations, resulting in 18 simulations using the default and 36 using the new hydrological scheme. This enabled the quantification of individual parameter and/or parameterisation uncertainties on model simulations and accounts for interactions between different parameterisations. The individual model parameterisations varied in this study are detailed below.

2.2.2 Hydrological parameterisation

We use two different representations of hydrology. The default soil hydrological scheme in CABLE simulates the exchange of water and heat based on six soil layers and up to three snow layers. The default parameterisation for soil moisture processes was developed by Kowalczyk et al. (1994) and later revised by Gordon et al. (2002) and is described in detail in Kowalczyk et al. (2006) and Wang et al. (2011). The default scheme only generates infiltration excess surface runoff when the top three soil layers are ≥ 95 % saturated and otherwise lacks an explicit runoff generation scheme (Decker, 2015). It does not distinguish between saturated and un-saturated top soil fractions or simulate groundwater dynamics. The default version of CABLE tends to overestimate Q_E at annual to seasonal scales when used coupled with the ACCESS climate model (Lorenz et al., 2014), but was found to significantly underestimate Q_E during soil moisture deficits across six European flux tower sites (De Kauwe et al., 2015c). It is not known if this is the result of the hydrological parameterisation and we explore this here.

Decker (2015) developed an improved representation of sub-surface hydrological processes similar to that implemented in the Community Land Model (Lawrence and Chase, 2007; Oleson et al., 2008). The new scheme simulates saturation- and infiltration-excess runoff generation and has a dynamic groundwater component with aquifer water storage. It also allows for sub-grid scale heterogeneity in soil moisture and has a modified soil evaporation formulation to reflect this. At point scales the runoff generation from sub-grid heterogeneity in soil moisture is neglected as the saturated fraction of the grid cell is assumed to be equal to zero. Decker (2015) showed that the new model reduced overestimations of Q_E by 50–70 % compared to the default scheme and yielded an improved simulation of seasonal cycles when evaluated against observations from large river basins.

The new hydrology scheme includes a slope parameter not present in the default model. This parameter controls the drainage rate and can in principle be constrained from high-resolution elevation data. We vary the slope parameter between 0 and 5°, broadly coinciding with the observed range of 0–6° at the flux sites as derived from the approximately 1 km spatial resolution Global 30-Arc Second Elevation (GTOPO30) elevation dataset (https://lta.cr.usgs.gov/GTOPO30).

HESSD
12, 10789–10825, 2015

2.2.3 Stomatal conductance parameterisation

We use two alternative parameterisations for stomatal conductance (g_s). The default CABLE currently implements an empirical g_s formulation following Leuning (1995). The Leuning model and similar empirical schemes (e.g. Ball et al., 1987) are widely used in LSMs but due to the empirical nature of these models we cannot attach any theoretical distinction to parameters across data sets or among species (De Kauwe et al., 2015b; Medlyn et al., 2011). Consequently, as is common with many LSMs, the default scheme only varies stomatal conductance parameters between photosynthetic pathways (C_3 vs. C_4), rather than among different PFTs.

As an alternative, we also ran CABLE using the g_s model following Medlyn et al. (2011), a theoretical formulation based on the premise of optimal stomatal behaviour. In contrast to the default scheme, g_s parameters have been derived for each of CABLE's PFTs (De Kauwe et al., 2015a) based on a global synthesis of stomatal behaviour (Lin et al., 2015). The Medlyn g_s model has been shown to improve existing CABLE biases, particularly overestimations of Q_E in evergreen needleleaf and C_4 biomes (De Kauwe et al., 2015a). The Leuning and Medlyn g_s models, as implemented in CABLE, are fully detailed in De Kauwe et al. (2015a).

2.2.4 Soil parameterisation

The soil parameters were derived from a dataset provided by CABLE developers (https://trac.nci.org.au/trac/cable/wiki; Global Soil Data Task Group, 2000). The dataset consists of nine soil classes; here the two classes with the highest sand and clay contents were used. The coarse sandy soil has a 87 % sand content and the fine clay soil a 66 % clay content; the soil classes have eight associated parameters for soil water holding and thermal capacities, fully detailed in Table S2. In addition, an arbitrary "medium" soil class was created with equal fractions of sand, silt and clay, with other soil parameters set as the median of the coarse sand and fine clay soil classes (Table S2). CABLE was run with these three alternative soil classes, fixing the soil param-

HESSD
12, 10789–10825, 2015

eters across all sites. The default hydrological scheme uses these three soil parameter sets directly, whereas the new scheme employs an empirical approach to calculate the parameters governing water holding and thermal capacities from sand, silt and clay fractions. The values used by both schemes are detailed in Table S2.

2.2.5 Leaf area index

Leaf area index (LAI) plays an important role in the surface energy balance in CABLE (Kala et al., 2014). LAI was obtained from 8-daily gridded Moderate Resolution Imaging Spectroradiometer (MODIS) data at 1 km resolution (Yuan et al., 2011). The data were averaged to monthly time steps to smooth the time series and subsequently three alternative LAI time series were created for each site to take some account of uncertainties in LAI inputs. The first time series was constructed by extracting the grid cells that contained each site ("centre" time series). Two alternative time series were created using the minimum and maximum LAI value of the grid cell and its immediate neighbours ("minimum" and "maximum" time series, respectively). Time-varying LAI was used for years where the flux observations and MODIS data overlap (i.e. after 2000); a monthly climatology of common years was used otherwise. The minimum and maximum time series differ from the centre time series by 30 % on average but the range varies between sites. The alternative LAI time series are plotted in Fig. S5.

2.3 Analysis methods

We analyse CABLE performance across three time scales: the whole observational, annual and sub-annual periods. As the observational records are generally short for characterising hydrological extremes (≤ 10 years, 5 years on average; Table S1), we have not adopted a formal statistical method for identifying periods of rainfall anomalies and thus do not refer to them as "droughts". We also note no one definition for droughts exists; instead, various indices have been employed based on for example, precipitation, streamflow and/or soil moisture (Sheffield and Wood, 2011). In this study,

HESSD
12, 10789–10825, 2015

the dry periods were defined based on precipitation as this allowed the use of available observations, but we note the simulated fluxes will also depend on other processes such as soil moisture availability. For the majority of sites (Howard Springs, Palang, and all supplementary sites), we selected the year with the lowest precipitation total as the one-year period, whilst for Amplero, Blodgett, Tumbarumba and UniMich, we selected a year when the default CABLE significantly underestimated latent heat fluxes during a rainfall deficit ("dry-down") period. The dry-down period generally coincides with the maximum and the following minimum observed latent heat flux during the one-year period but has been adjusted for some sites to best capture typical model behaviour (Fig. S6). Observed and simulated data were averaged to 14 day running means for all analyses.

We follow PALS for calculating model metrics. We use the normalised mean error (NME) to evaluate general model performance:

$$\mathrm{NME} = \frac{\sum_{i=1}^{n} |M_i - O_i|}{\sum_{i=1}^{n} |\overline{O} - O_i|} \quad (1)$$

where M represents the model values and O the observations. NME accounts for mean model biases and the temporal coincidence and magnitude of variability, but does not distinguish between them (Best et al., 2015). An NME of 0.0 represents perfect agreement and a value of 1.0 represents model performance equal to that expected from a constant value equal to the mean of all observations.

We examine mean bias error (MBE) to estimate absolute biases in CABLE simulations; it is simply the difference between the mean modelled and observed values:

$$\mathrm{MBE} = \overline{M} - \overline{O}. \quad (2)$$

HESSD
12, 10789–10825, 2015

3 Results

3.1 Whole time period

We first evaluated CABLE-simulated Q_E during the whole data period available for each flux site (ranging from 2 to 7 years for selected sites; Table S1). CABLE, using the default hydrological parameterisation, captures the general features, such as the timing and magnitude of seasonal cycles, in observed Q_E across the different sites (Fig. 2, left column). CABLE including the new hydrological scheme also captures these general features (Fig. 2, right column). Quantifying the performance of these two versions of CABLE over the full length of record does not indicate that there is a significant difference between the versions in either NME (Fig. 3) or MBE (Fig. 4). The average NME for all sites and parameter choices was 0.90 for the old scheme and 0.75 for the new scheme, and the average MBE was −1 and 6 $W m^{-2}$, respectively. The NME metric is < 1.0 for the majority of sites using the new scheme, regardless of the choice of g_s, LAI or soil parameterisation. We note that the magnitude of Q_E for the evergreen broadleaf sites (Palang and Tumbarumba and supplementary site Espirra) is poorly captured (Fig. 4). Overall, both hydrological parameterisations tend to overestimate peak Q_E (Fig. 2); this tendency for excessive evapotranspiration has also been demonstrated in global applications of CABLE in both offline (De Kauwe et al., 2015a) and coupled (Lorenz et al., 2014) simulations. Furthermore, both schemes systematically overestimate Q_E in spring, particularly at cooler temperate sites such as UniMich (Fig. 2; also see deciduous broadleaf and needleleaf supplementary sites – Fig. S1), and over-predict the short-term variability in Q_E (see e.g. Amplero in Fig. 2). This is likely due to overly rapid drying of top soil layers, which strongly control Q_E in CABLE (De Kauwe et al., 2015c). This is particularly evident during warmer summer months when fluxes are more strongly moisture-limited (see e.g. Tumbarumba and UniMich in Fig. 2). Despite clear biases in simulated fluxes, the MBE metric approaches zero at most sites when evaluated at inter-annual time scales. While encouraging, this is likely due to compensating errors, such that early season overestimations in Q_E are

HESSD
12, 10789–10825, 2015

counteracted by underestimations during the dry-down periods. This is particularly evident with the default hydrology scheme. We therefore focus the remaining analyses on shorter time periods where compensating biases are less likely to hide weaknesses in the model performance.

3.2 Annual and dry-down period

CABLE-simulated Q_E were then evaluated during annual and seasonal dry-down periods to explore model performance during rainfall deficits. The default scheme demonstrates a range of major biases (Fig. 5). The model dries down too quickly at Amplero, Blodgett, Palang, Tumbarumba and UniMich sites. At these sites and at Howard Springs, Q_E drops too low and drops to that minimum too early in the year. At several sites, including Blodgett, Tumbarumba and UniMich, CABLE systematically overestimates Q_E in spring. These characteristics of CABLE are not dependent on the choice of LAI, g_s, or soil parameters; the range in Q_E fails to overlap the observations irrespective of how these properties are varied.

The new hydrological scheme demonstrates clear improvements at Amplero, Howard Springs and Palang. At Blodgett, Tumbarumba and UniMich, the observations are within the uncertainty due to the choice of g_s, LAI or soil parameters in the second half of the year, but the excessive Q_E during spring and early summer remains a problem. While there are obviously remaining errors, the new hydrological scheme clearly improves the simulation of Q_E over the annual cycles shown in Fig. 5. Assessing the overall performance at annual time scales also highlights clear improvements with the new hydrology. Figure 3 shows that for NME, the new hydrology scheme in CABLE performs as well as, or better than the default at every site, with an average NME across all sites of 0.68 compared to 0.90 for the default scheme. This is true also of MBE (Fig. 4) for all sites except Tumbarumba.

Assessing the performance of the two schemes over the dry-down period using NME is shown in Fig. 5. Using the default hydrology leads to worse performance on this shorter time scale at Amplero, Blodgett, Palang and to a lesser degree at Howard

HESSD
12, 10789–10825, 2015

Springs and Tumbarumba compared to annual and inter-annual scales. In contrast, CABLE with the new hydrology performs similarly well to the longer (≥ 1 year) time scales at Blodgett, Palang, Howard Springs, Tumbarumba and UniMich and only marginally poorer at Amplero. Comparing NME over this dry down period shows that the new scheme strongly outperforms the default parameterisation (Fig. 3; the average NME is 0.68 and 1.27 for new and default schemes, respectively). A similar conclusion is reached using MBE (on average −4 and −22 $W\,m^{-2}$ for the new and default schemes, respectively). In short, the new hydrology does not dramatically improve the performance of CABLE on the long term (i.e. inter-annual scales) (Fig. 2) due to compensating biases in the default CABLE. These include overestimated spring and early summer Q_E, and consequently, at least in part, underestimated Q_E during the dry-down. Once we focus on shorter, sub-annual timescales that lack these compensating biases, CABLE with the new hydrology strongly outperforms the default version in the simulation of Q_E.

3.3 Impact of varying LAI, g_s and soil parameters

We now explore the individual contributions from soil parameters, g_s and LAI to uncertainties in simulated Q_E. Figures 6 and 7 show the uncertainty in model simulations due to soil parameters, g_s and LAI using the default and new hydrological schemes, respectively. Both hydrological schemes are sensitive to soil parameters during the dry-down period but show smaller variations due to soil during other parts of the year (see Amplero, Blodgett, Howard Springs and Palang in Figs. 6 and 7). This transition from low to high sensitivity occurs as soil moisture stores begin to deplete and Q_E becomes increasingly limited by moisture supply. The new hydrological scheme uses a narrower range of parameter values for water holding capacity and conductivity (Table S2) and thus results in a smaller range of uncertainty due to soil parameters. Both schemes show a similar sensitivity to g_s and LAI variations, which is generally smaller compared to soil variations, although the new scheme is more sensitive to g_s at Blodgett, Howard Springs and Palang, and to LAI in Amplero and Palang during dry-down.

While the new hydrological parameterisation systematically improved model performance across most sites (Figs. 3 and 4), the effect of LAI, g_s and soil parameters on the mean magnitude of simulated fluxes is highly site-specific during the annual and dry-down periods (Fig. 8). In agreement with De Kauwe et al. (2015a), the choice of g_s scheme generally has a larger effect in needleleaf (Blodgett) and C_4 grass (Howard Springs) sites. Some sites, such as Howard Springs, are sensitive to multiple parameters, whilst others such as UniMich only respond minimally to parameter perturbations (Fig. 8). Whilst there is no a priori expectation that this should be the case, it highlights the importance of investigating model uncertainties and performance across multiple sites to capture full range of model sensitivities to parameter perturbations.

The results have so far assessed CABLE when incorporating the new hydrology using a 0° slope parameter because this enables a direct comparison with the default hydrology. The slope parameter, which can be derived from high-resolution elevation data, is scale dependent and was introduced by Decker (2015) to capture large-scale hydrological processes that are affected by landscape geometry. The slope parameter affects the rate of subsurface drainage and represents a key difference between the new and default schemes. With the exception of the UniMich site, Figs. 8 and 9 show that the model is highly sensitive to choice of the slope parameter across all sites, particularly during the dry-down period. The slope appears more critical for simulation of Q_E than the other parameterisations investigated here and has a strong effect on the magnitude of fluxes primarily during the dry-down (see e.g. Howard Springs and Palang in Fig. 9). Whilst this highlights the need to carefully set the slope parameter, it is unclear how well it can be constrained at the site scale. The surface slope derived from elevation data may not reflect large-scale features, such as subsurface geology, which can affect drainage rates and thus water availability for Q_E in highly site-specific ways.

HESSD
12, 10789–10825, 2015

4 Discussion

4.1 Simulation of dry-down

We have shown that the default version of CABLE significantly underestimates Q_E during rainfall deficits. We have also shown that it is unlikely that uncertainties in key model soil and vegetation (LAI) inputs, account for these biases. Instead, our results point to deficiencies in the representation of hydrological processes in the default version of CABLE. The default CABLE has been shown to perform similarly to other LSMs in Best et al. (2015) and indeed in other model evaluation studies (Abramowitz et al., 2008). Hence, it is likely that the errors of the kind identified here may be common among other models. The poor simulation of dry-down periods is important: if LSMs in general struggle to simulate the dry-down period they will fail to correctly capture water fluxes when serious soil moisture deficits are established. A model that dries down too fast will enter drought early and will tend to simulate longer, deeper and more frequent droughts than a model that dries down too slowly. We suggest that systematic evaluation of LSMs during dry down periods would lead to the identification of major limitations in some models that are hidden by compensating errors over longer timescales. Resolution of those problems has the potential to improve the simulation of drought in climate models.

We also showed the effect of individual parameterisations was magnified during dry periods. Whilst the new hydrological scheme did not have a significant impact on the annual and inter-annual timescales analysed here, it had an increasingly large positive impact on shorter time scales and in particular during the dry-down periods. Similarly, the contribution of LAI, g_s and soil parameterisations to model uncertainties was generally larger during the dry-down. This highlights the value of evaluating model parameterisations against both mean and (more) extreme states. It also points to the challenge that, in these dry down periods that are critical to how a landscape develops towards drought, the skill needed to capture the relevant processes will be higher than during wet periods.

HESSD

12, 10789–10825, 2015

4.2 Overestimation of soil evaporation

We identified systematic biases in the simulation of peak and spring Q_E, particularly at forested sites (e.g. Tumbarumba and Blodgett). Both hydrological schemes showed a tendency to significantly overestimate these fluxes. The reason for the overestimation of peak fluxes is not clear but is not resolved by the new hydrological scheme despite this parameterising many of the relevant processes differently. The high Q_E in spring is associated with excessive soil evaporation and is not linked to transpiration, which closely follow the observed seasonal cycle (Fig. S7).

There are multiple potential causes and solutions to this excessive $Q_{E.}$ Haverd and Cuntz (2010) showed the inclusion of litter layer dynamics in CABLE improved the simulated timing of spring Q_E at Tumbarumba by suppressing soil evaporation but this was not implemented in the current study. Adding a litter layer may resolve excessive soil evaporation at forested sites by adding an additional resistance to evaporation, but is unlikely to resolve errors for other PFTs. However, before we attempt to implement litter dynamics, we need to be sure that this addition is not simply masking a major deficiency elsewhere in the model. For example, errors in the timing of spring green-up at deciduous sites in the LAI inputs (e.g. Fisher and Mustard, 2007) may contribute to excessive spring evaporation, whereby a delayed green-up would allow excessive radiation to reach the ground surface in early spring, increasing soil evaporation rates. Insufficient drainage, and consequently overestimated surface soil moisture, and/or insufficient reduction of soil evaporation during soil drying may also explain the excess spring Q_E. Alternatively, high soil evaporation may result from the simulation of excessive within canopy turbulence (Raupach, 1989a, b, 1994). The biases in the timing and magnitude of spring and peak fluxes not only have implications for the correct simulation of seasonal cycles, but may also affect the magnitude of dry-down simulated by the model. The excessive spring and early summer Q_E may reduce soil moisture levels prior to the dry-down, leading to the simulation of more severe reductions in Q_E during dry periods.

HESSD
12, 10789–10825, 2015

Our strategy to resolve the excessive spring soil evaporation is linked with the Best et al. (2015) experimental protocol. Using multi-LSM simulations we hope to be able to identify where CABLE is anomalous, and ideally implement the model parameterisations used in other LSMs that do not simulate excessive spring soil evaporation.

4.3 Further model uncertainties

In this study, we explored and quantified model uncertainties due to LAI, g_s, hydrological and soil parameters, limiting our analysis to parameters that can be derived from observationally based global datasets (despite considerable uncertainties). Other model processes, particularly vegetation response to drought, have been identified as critical for capturing drought processes and shown to improve CABLE performance during droughts but were not explored here. The simulation of the effects of soil moisture limitation on photosynthesis and stomatal conductance remains a key uncertainty for drought responses in LSMs (Zhou et al., 2013). Models rely on differing assumptions about the effects of water stress on photosynthesis and stomatal conductance (Egea et al., 2011; Keenan et al., 2009) but generally assume similar drought responses across different PFTs (including CABLE as employed here) (De Kauwe et al., 2015c; Zhou et al., 2013). De Kauwe et al. (2015b) evaluated CABLE against flux site observations during the 2003 European drought using an alternative drought model with experimentally derived drought sensitivities. The authors similarly showed significant underestimations of Q_E using the default CABLE but these were improved using different plant species sensitivities to drought and a dynamic weighting of water uptake across soil layers. Experimental data to inform the parameterisation of PFT-specific drought responses, however, remains limited (De Kauwe et al., 2015c), complicating the implementation of such responses into LSMs. Li et al. (2012) showed the underestimation of CABLE-simulated Q_E under water-stressed conditions could be improved by employing an alternative root water uptake scheme. The default root water uptake function in CABLE employed here (Wang et al., 2011) assumes a constant efficiency of water uptake per unit root length (Li et al., 2012). CABLE with the alternative scheme, combining a function allowing variable root-density distribution (Lai and Katul, 2000) with a hydraulic redistribution scheme (which allows roots to move water from wetter to drier soil layers), was shown to correctly capture the magnitude of seasonal droughts across three flux tower sites. The implementation of more realistic vegetation responses and adaptations to droughts should further refine the performance of the new hydrological scheme during dry-down periods.

Furthermore, in current simulations prescribed monthly MODIS LAI was used. Whilst CABLE and many other LSMs are capable of simulating LAI dynamically, it is common practice, particularly in coupled online simulations, to rely on prescribed monthly climatology instead of time-varying LAI. This limits the realistic simulation of reductions in LAI during severe droughts and consequent feedbacks with radiative and evaporative processes such as interception losses. Canopy defoliation may, for example, decrease transpiration and interception but also increase radiation reaching the soil surface, potentially increasing soil evaporation in the presence of available moisture, whilst also decreasing albedo and total ground-reaching radiation. As these feedbacks were not considered in this study, the rate of dry-down may have been overestimated at sites which experienced LAI reductions during rainfall deficits, but which may not have been captured in the MODIS LAI inputs. However, as only the magnitude of LAI was varied in this study, it is not possible to quantify the effects of temporal errors in LAI on simulated Q_E. But as both hydrological models were forced with identical LAI, it is unlikely uncertainties in the prescribed LAI explain the excessive dry-down in the default hydrological scheme.

We have limited our analysis to short-term, seasonal-scale rainfall deficits. Multi-annual droughts, such as the Millennium drought in eastern Australia (van Dijk et al., 2013), are likely to exhibit different dynamics in terms of vegetation responses and consequent feedbacks with land surface fluxes, soil moisture states and albedo. Prudhomme et al. (2011), for example, showed the JULES LSM to more successfully reproduce long-term hydrological droughts than short-term events in terms of duration and severity. Realistic representations of plant adaptations to drought and dynamically varying LAI are likely to be increasingly important for representing vegetation resilience and coupled land surface processes during long-term droughts. We therefore suggest future studies of LSM performance under water-stressed conditions should evaluate models against drought events at different temporal scales.

5 Conclusions

This study has evaluated the CABLE land surface model for seasonal-scale precipitation deficits using 20 flux tower sites distributed globally. We varied the soil hydrological and stomatal conductance parameterisations, and the inputs for LAI and soil properties. Our goal was to determine whether CABLE can capture dry-down associated with rainfall deficits as these components of the model are varied, or whether the model lacks the mechanisms to simulate this phenomenon.

On long time scales (annual and above), compensating biases mean that the two versions of CABLE did not perform very differently. However, as our analysis focused on periods of rainfall deficit, a new hydrological parameterisation based on Decker (2015) clearly improved the capability of CABLE to simulate Q_E. However, neither version of CABLE, and no reasonable choice of soil parameter, LAI or stomatal conductance resolved systematic seasonal-scale biases in excessive spring soil evaporation. The reasons for these biases cannot be determined in isolation and we will next pursue these model limitations using the PLUMBER multi-model benchmarking framework (Best et al., 2015).

Our study highlights some opportunities for land modellers. First, our study again demonstrates the value in freely-available flux tower data for identifying systematic biases in LSMs. The value of these data extends well beyond their common use in evaluating means or seasonal cycles. Second, a major role for LSMs is to simulate feedbacks to the atmosphere associated with rainfall deficits. We have demonstrated that there is skill in CABLE in simulating these feedbacks as a landscape dries but clearly more work needs to be invested in capturing all the elements of a drying soil and its impacts on Q_E. While the parameterisation of hydrology has been explored over the years, we remind the community that there are on-going challenges in modelling soil moisture and links between soil moisture and evaporation that are not yet resolved. Third, we note that CABLE performs comparatively relative to other LSMs (Abramowitz et al., 2007; Best et al., 2015) and yet when we interrogate the model's performance at timescales when compensating biases are limited, CABLE displays some concerning behaviour. It is inevitable that other LSMs, if examined using these periods of precipitation deficit, will also exhibit problems. Clearly, formally testing LSMs against more extreme conditions, and in the context of specific phenomenon (e.g. drought or heatwave) is a necessary step to build confidence in the projections from climate models that utilise LSMs.

The Supplement related to this article is available online at doi:10.5194/hessd-12-10789-2015-supplement.

Acknowledgements. We acknowledge the support of the Australian Research Council Centre of Excellence for Climate System Science (CE110001028). M. De Kauwe was supported by the Australian Research Council Linkage grant LP140100232. This work used eddy covariance data acquired by the FLUXNET community and in particular by the following networks: AmeriFlux (U.S. Department of Energy, Biological and Environmental Research, Terrestrial Carbon Program (DE-FG02-04ER63917 and DE-FG02-04ER63911)), AfriFlux, AsiaFlux, CarboAfrica, CarboEuropeIP, CarboItaly, CarboMont, ChinaFlux, Fluxnet-Canada (supported by CFCAS, NSERC, BIOCAP, Environment Canada, and NRCan), GreenGrass, KoFlux, LBA, NECC, OzFlux, TCOS-Siberia, USCCC. We acknowledge the financial support to the eddy covariance data harmonization provided by CarboEuropeIP, FAO-GTOS-TCO, iLEAPS, Max Planck Institute for Biogeochemistry, National Science Foundation, University of Tuscia, Universiteì Laval and Environment Canada and US Department of Energy and the database development and technical support from Berkeley Water Center, Lawrence Berkeley National Laboratory, Microsoft Research eScience, Oak Ridge National Laboratory, University of California – Berkeley, University of Virginia.

References

Abramowitz, G.: Towards a public, standardized, diagnostic benchmarking system for land surface models, Geosci. Model Dev., 5, 819–827, doi:10.5194/gmd-5-819-2012, 2012.

Abramowitz, G., Pitman, A., Gupta, H., Kowalczyk, E., and Wang, Y.: Systematic bias in land surface models, J. Hydrometeorol., 8, 989–1001, doi:10.1175/JHM628.1, 2007.

Abramowitz, G., Leuning, R., Clark, M., and Pitman, A.: Evaluating the performance of land surface Models, J. Climate, 21, 5468–5481, doi:10.1175/2008JCLI2378.1, 2008.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J. H., Allard, G., Running, S. W., Semerci, A., and Cobb, N.: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, Forest Ecol. Manage., 259, 660–684, doi:10.1016/j.foreco.2009.09.001, 2010.

Ball, T., Woodrow, I., and Berry, J.: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, in: Progress in photosynthesis research, edited by: Biggins, J., Martinus Nijhoff, Leiden, the Netherlands, 221–224, 1987.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R.L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geosci. Model Dev., 4, 677–699, doi:10.5194/gmd-4-677-2011, 2011.

Best, M. J., Abramowitz, G., Johnson, H. R., Pitman, A. J., Balsamo, G., Boone, A., Cuntz, M., Decharme, B., Dirmeyer, P. A., Dong, J., Ek, M., Guo, Z., Haverd, V., van den Hurk, B. J.., Nearing, G. S., Pak, B., Peters-Lidard, C., Santanello, J. A., Stevens, L., and Vuichard, N.: The plumbing of land surface models: benchmarking model performance, J. Hydrometeorol., 16, 1425–1422, doi:10.1175/JHM-D-14-0158.1, 2015.

Bi, D., Dix, M., Marsland, S. J., O'Farrell, S., Rashid, H. a, Uotila, P., Hirst, A. C., Kowalczyk, E., Golebiewski, M., Sullivan, A., Yan, H., Hannah, N., Franklin, C., Sun, Z., Vohralik, P., Watterson, I., Zhou, X., Fiedler, R., Collier, M., Ma, Y., Noonan, J., Stevens, L., Uhe, P., Zhu, H., Griffies, S. M., Hill, R., Harris, C., Puri, K., and Farrell, S. O.: The ACCESS coupled model: description, control climate and evaluation, Aust. Meteorol. Oceanogr. J., 63, 41–64, 2013.

HESSD
12, 10789–10825, 2015

Modelling evapotranspiration during precipitation deficits

A. M. Ukkola et al.

Blyth, E., Clark, D. B., Ellis, R., Huntingford, C., Los, S., Pryor, M., Best, M., and Sitch, S.: A comprehensive set of benchmark tests for a land surface model of simultaneous fluxes of water and carbon at both the global and seasonal scale, Geosci. Model Dev., 4, 255–269, doi:10.5194/gmd-4-255-2011, 2011.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 1029–1136, 2013.

Cruz, F. T., Pitman, A. J., McGregor, J. L., and Evans, J. P.: Contrasting regional responses to increasing leaf-level atmospheric carbon dioxide over Australia, J. Hydrometeorol., 11, 296–314, doi:10.1175/2009jhm1175.1, 2010.

Dai, A.: Drought under global warming: a review, Wiley Interdiscip. Rev. Clim. Change, 2, 45–65, doi:10.1002/wcc.81, 2011.

Dai, A.: Increasing drought under global warming in observations and models, Nat. Clim. Change, 3, 52–58, doi:10.1038/nclimate1633, 2012.

Decker, M.: Development and Evaluation of a new Soil Moisture and Runoff Parameterization for the CABLE LSM including subgrid scale processes, J. Adv. Model. Earth Syst., accepted, 2015.

De Kauwe, M. G., Kala, J., Lin, Y.-S., Pitman, A. J., Medlyn, B. E., Duursma, R. A., Abramowitz, G., Wang, Y.-P., and Miralles, D. G.: A test of an optimal stomatal conductance scheme within the CABLE land surface model, Geosci. Model Dev., 8, 431–452, doi:10.5194/gmd-8-431-2015, 2015a.

De Kauwe, M. G., Kala, J., Lin, Y.-S., Pitman, A. J., Medlyn, B. E., Duursma, R. A., Abramowitz, G., Wang, Y.-P., and Miralles, D. G.: A test of an optimal stomatal conductance scheme within the CABLE land surface model, Geosci. Model Dev., 8, 431–452, doi:10.5194/gmd-8-431-2015, 2015b.

De Kauwe, M. G., Zhou, S.-X., Medlyn, B. E., Pitman, A. J., Wang, Y.-P., Duursma, R. A., and Prentice, I. C.: Do land surface models need to include differential plant species responses

HESSD
12, 10789–10825, 2015

to drought? Examining model predictions across a latitudinal gradient in Europe, Biogeosciences Discuss., 12, 12349–12393, doi:10.5194/bgd-12-12349-2015, 2015c.
Dirmeyer, P. A.: A History and review of the Global Soil Wetness Project (GSWP), J. Hydrometeorol., 12, 729–749, doi:10.1175/JHM-D-10-05010.1, 2011.
Egea, G., Verhoef, A., and Vidale, P. L.: Towards an improved and more flexible representation of water stress in coupled photosynthesis-stomatal conductance models, Agr. Forest Meteorol., 151, 1370–1384, doi:10.1016/j.agrformet.2011.05.019, 2011.
Fisher, J. I. and Mustard, J. F.: Cross-scalar satellite phenology from ground, Landsat, and MODIS data, Remote Sens. Environ., 109, 261–273, doi:10.1016/j.rse.2007.01.004, 2007.
Global Soil Data Task Group: Global gridded surfaces of selected soil characteristics (IGBP-IDS), available at: http://www.daac.ornl.gov (last access: 20 October 2015), 2000.
Gordon, H. B., Rotstayn, L. D., McGregor, J. L., Dix, J. L., Kowalczyk, E. A., O'Farrell, S. P., Waterman, L. J., Hirst, A. C., Wilson, S. G., Collier, M. A., Watterson, I. G., and Elliott, T. I.: The CSIRO Mk3 Climate System Model, Aspendale, Victoria, Australia, 2002.
Gupta, H. V., Bastidas, L. A., Sorooshian, S., Shuttleworth, W. J., and Yang, Z. L.: Parameter estimation of a land surface scheme using multicriteria methods, J. Geophys. Res., 104, 19491–19503, doi:10.1029/1999JD900154, 1999.
Haverd, V. and Cuntz, M.: Soil-Litter-Iso: a one-dimensional model for coupled transport of heat, water and stable isotopes in soil with a litter layer and root extraction, J. Hydrol., 388, 438–455, doi:10.1016/j.jhydrol.2010.05.029, 2010.
Haverd, V., Raupach, M. R., Briggs, P. R., Canadell, J. G., Isaac, P., Pickett-Heaps, C., Roxburgh, S. H., van Gorsel, E., Viscarra Rossel, R. A., and Wang, Z.: Multiple observation types reduce uncertainty in Australia's terrestrial carbon and water cycles, Biogeosciences, 10, 2011–2040, doi:10.5194/bg-10-2011-2013, 2013.
Henderson-Sellers, A., Pitman, A., Love, P., Irannejad, P., and Chen, T.: The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS): phases 2 and 3, B. Am. Meteorol. Soc., 76, 489–503, 1995.
Huang, M., Piao, S., Sun, Y., Ciais, P., Cheng, L., Mao, J., Poulter, B., Shi, X., Zeng, Z., and Wang, Y.: Change in terrestrial ecosystem water-use efficiency over the last three decades, Global Change Biol., 21, 2366–2378, doi:10.1111/gcb.12873, 2015.
IPCC: Climate Change 2013: The Physical Science Basis, in: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A.,

Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.
Kala, J., Decker, M., Exbrayat, J.-F., Pitman, A. J., Carouge, C., Evans, J. P., Abramowitz, G., and Mocko, D.: Influence of Leaf area index prescriptions on simulations of heat, moisture, and carbon fluxes, J. Hydrometeorol., 15, 489–503, doi:10.1175/JHM-D-13-063.1, 2014.
Keenan, T., García, R., Friend, A. D., Zaehle, S., Gracia, C., and Sabate, S.: Improved understanding of drought controls on seasonal variation in Mediterranean forest canopy CO_2 and water fluxes through combined in situ measurements and ecosystem modelling, Biogeosciences Discuss., 6, 2285–2329, doi:10.5194/bgd-6-2285-2009, 2009.
Koster, R. D., Guo, Z., Yang, R., Dirmeyer, P. A., Mitchell, K., and Puma, M. J.: On the nature of soil moisture in land surface models, J. Climate, 22, 4322–4335, doi:10.1175/2009JCLI2832.1, 2009.
Kowalczyk, E. A., Garratt, J. R., and Krummel, P. B.: Implementation of a soil-canopy scheme into the CSIRO GCM: regional aspects of the model response, Technical Paper no. 32, CSIRO Division of Atmospheric Research, Aspendale, Victoria, Australia, 1994.
Kowalczyk, E. A., Wang, Y. P., Law, R. M., Davies, H. L., Mcgregor, J. L., and Abramowitz, G.: The CSIRO Atmosphere Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model, Aspendale, Victoria, Australia, 2006.
Lai, C.-T. and Katul, G.: The dynamic role of root-water uptake in coupling potential to actual transpiration, Adv. Water Resour., 23, 427–439, doi:10.1016/S0309-1708(99)00023-8, 2000.
Lawrence, P. J. and Chase, T. N.: Representing a new MODIS consistent land surface in the Community Land Model (CLM 3.0), J. Geophys. Res.-Biogeo., 112, G01023, doi:10.1029/2006JG000168, 2007.
Leplastrier, M., Pitman, A., Gupta, H., and Xia, Y.: Exploring the relationship between complexity and performance in a land surface model using the multicriteria method, J. Geophys. Res., 107, 1–12, doi:10.1029/2001JD000931, 2002.
Leuning, R.: A critical appraisal of a combined stomatal-photosynthesis model for C_3 plants, Plant. Cell Environ., 18, 339–355, 1995.
Li, L., Wang, Y.-P., Yu, Q., Pak, B., Eamus, D., Yan, J., van Gorsel, E., and Baker, I. T.: Improving the responses of the Australian community land surface model (CABLE) to seasonal drought, J. Geophys. Res., 117, G04002, doi:10.1029/2012JG002038, 2012.

HESSD
12, 10789–10825, 2015

Modelling evapotranspiration during precipitation deficits

A. M. Ukkola et al.

Lin, Y.-S., Medlyn, B. E., Duursma, R. A., Prentice, I. C., Wang, H., Baig, S., Eamus, D., de Dios, V. R., Mitchell, P., Ellsworth, D. S., de Beeck, M. O., Wallin, G., Uddling, J., Tarvainen, L., Linderson, M.-L., Cernusak, L. A., Nippert, J. B., Ocheltree, T. W., Tissue, D. T., Martin-StPaul, N. K., Rogers, A., Warren, J. M., De Angelis, P., Hikosaka, K., Han, Q., Onoda, Y., Gimeno, T. E., Barton, C. V. M., Bennie, J., Bonal, D., Bosc, A., Löw, M., Macinins-Ng, C., Rey, A., Rowland, L., Setterfield, S. A., Tausz-Posch, S., Zaragoza-Castells, J., Broadmeadow, M. S. J., Drake, J. E., Freeman, M., Ghannoum, O., Hutley, L. B., Kelly, J. W., Kikuzawa, K., Kolari, P., Koyama, K., Limousin, J.-M., Meir, P., Lola da Costa, A. C., Mikkelsen, T. N., Salinas, N., Sun, W., and Wingate, L.: Optimal stomatal behaviour around the world, Nat. Clim. Change, 5, 459–464, doi:10.1038/nclimate2550, 2015.

Lorenz, R. and Pitman, A. J.: Effect of land–atmosphere coupling strength on impacts from Amazonian deforestation, Geophys. Res. Lett., 41, 5987–5995, doi:10.1002/2014GL061017, 2014.

Lorenz, R., Pitman, A. J., Donat, M. G., Hirsch, A. L., Kala, J., Kowalczyk, E. A., Law, R. M., and Srbinovsky, J.: Representation of climate extreme indices in the ACCESS1.3b coupled atmosphere–land surface model, Geosci. Model Dev., 7, 545–567, doi:10.5194/gmd-7-545-2014, 2014.

Medlyn, B. E., Duursma, R. A., Eamus, D., Ellsworth, D. S., Prentice, I. C., Barton, C. V. M., Crous, K. Y., De Angelis, P., Freeman, M., and Wingate, L.: Reconciling the optimal and empirical approaches to modelling stomatal conductance, Global Change Biol., 17, 2134–2144, doi:10.1111/j.1365-2486.2010.02375.x, 2011.

Oleson, K. W., Niu, G. Y., Yang, Z. L., Lawrence, D. M., Thornton, P. E., Lawrence, P. J., Stöckli, R., Dickinson, R. E., Bonan, G. B., Levis, S., Dai, A., and Qian, T.: Improvements to the community land model and their impact on the hydrological cycle, J. Geophys. Res.-Biogeo., 113, blackboxPlease provide page range or article number., doi:10.1029/2007JG000563, 2008.

Pitman, A. J.: The evolution of, and revolution in, land surface schemes designed for climate models, Int. J. Climatol., 23, 479–510, doi:10.1002/joc.893, 2003.

Powell, T. L., Galbraith, D. R., Christoffersen, B. O., Harper, A., Imbuzeiro, H. M. a, Rowland, L., Almeida, S., Brando, P. M., da Costa, A. C. L., Costa, M. H., Levine, N. M., Malhi, Y., Saleska, S. R., Sotta, E., Williams, M., Meir, P., and Moorcroft, P. R.: Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought, New Phytol., 200, 350–365, doi:10.1111/nph.12390, 2013.

Prudhomme, C., Parry, S., Hannaford, J., Clark, D. B., Hagemann, S., and Voss, F.: How well do large-scale models reproduce regional hydrological extremes in Europe?, J. Hydrometeorol., 12, 1181–1204, doi:10.1175/2011JHM1387.1, 2011.
Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., Fekete, B. M., Franssen, W., Gerten, D., Gosling, S. N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment, P. Natl. Acad. Sci. USA, 111, 3262–7, doi:10.1073/pnas.1222473110, 2014.
Puri, K., Dietachmayer, G., Steinle, P., Dix, M., Rikus, L., Logan, L., Naughton, M., Tingwell, C., Xiao, Y., Barras, V., Bermous, I., Bowen, R., Deschamps, L., Franklin, C., Fraser, J., Glowacki, T., Harris, B., Lee, J., Le, T., Roff, G., Sulaiman, a, Sims, H., Sun, X., Sun, Z., Zhu, H., Chattopadhyay, M., and Engel, C.: Implementation of the initial ACCESS numerical weather prediction system, Aust. Meteorol. Oceanogr. J., 63, 265–284, 2013.
Raupach, M. R.: A practical Lagrangian method for relating scalar concentrations to source distributions in vegetation canopies, Q. J. Roy. Meteorol. Soc., 115, 609–632, doi:10.1002/qj.49711548710, 1989a.
Raupach, M. R.: Applying Lagrangian fluid mechanics to infer scalar source distributions from concentration profiles in plant canopies, Agr. Forest Meteorol., 47, 85–108, doi:10.1016/0168-1923(89)90089-0, 1989b.
Raupach, M. R.: Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index, Bound.-Lay. Meteorol., 71, 211–216, doi:10.1007/BF00709229, 1994.
Sheffield, J. and Wood, E.: Drought: Past Problems and Future Scenarios, Earthscan, London, UK, 2011.
Trenberth, K. E., Dai, A., Schrier, G. Van Der, Jones, P. D., Barichivich, J., Briffa, K. R., and Sheffield, J.: Global warming and changes in drought, Nat. Clim. Change, 4, 17–22, doi:10.1038/NCLIMATE2067, 2014.
van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R. A. M., Liu, Y. Y., Podger, G. M., Timbal, B., and Viney, N. R.: The Millennium Drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society, Water Resour. Res., 49, 1–18, doi:10.1002/wrcr.20123, 2013.

HESSD
12, 10789–10825, 2015

Wang, K. and Dickinson, R. E.: A review of global terrestrial evapotranspiration: observation, modeling, climatology and climatic variability, Rev. Geophys., 50, RG2005, doi:10.1029/2011RG000373, 2012.
Wang, Y. and Leuning, R.: A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I?: model description and comparison with a multi-layered model, Agr. Forest Meteorol., 91, 89–111, 1998.
Wang, Y. P., Leuning, R., Cleugh, H., and Coppin, P.: Parameter estimation in surface exchange models using nonlinear inversion?: how many parameters can we estimate and which measurements are most useful?, Global Change Biol., 7, 495–510, doi:10.1046/j.1365-2486.2001.00434.x, 2001.
Wang, Y. P., Kowalczyk, E., Leuning, R., Abramowitz, G., Raupach, M. R., Pak, B., van Gorsel, E., and Luhar, A.: Diagnosing errors in a land surface model (CABLE) in the time and frequency domains, J. Geophys. Res., 116, G01034, doi:10.1029/2010JG001385, 2011.
Williams, M., Richardson, A. D., Reichstein, M., Stoy, P. C., Peylin, P., Verbeeck, H., Carvalhais, N., Jung, M., Hollinger, D. Y., Kattge, J., Leuning, R., Luo, Y., Tomelleri, E., Trudinger, C. M., and Wang, Y. -P.: Improving land surface models with FLUXNET data, Biogeosciences, 6, 1341–1359, doi:10.5194/bg-6-1341-2009, 2009.
Yuan, H., Dai, Y., Xiao, Z., Ji, D., and Shangguan, W.: Reprocessing the MODIS leaf area index products for land surface and climate modelling, Remote Sens. Environ., 115, 1171–1187, doi:10.1016/j.rse.2011.01.001, 2011.
Zhang, H., Pak, B., Wang, Y. P., Zhou, X., Zhang, Y., and Zhang, L.: Evaluating surface water cycle simulated by the australian community land surface model (CABLE) across different spatial and temporal domains, J. Hydrometeorol., 14, 1119–1138, doi:10.1175/JHM-D-12-0123.1, 2013.
Zhou, S., Duursma, R. A., Medlyn, B. E., Kelly, J. W. G., and Prentice, I. C.: How should we model plant responses to drought? An analysis of stomatal and non-stomatal responses to water stress, Agr. Forest Meteorol., 182–183, 204–214, doi:10.1016/j.agrformet.2013.05.009, 2013.
Zhou, X., Zhang, Y., Wang, Y., Zhang, H., Vaze, J., Zhang, L., Yang, Y., and Zhou, Y.: Benchmarking global land surface models against the observed mean annual runoff from 150 large basins, J. Hydrol., 470–471, 269–279, doi:10.1016/j.jhydrol.2012.09.002, 2012.

Figure 1. Location of selected and supplementary flux tower sites.

HESSD
12, 10789–10825, 2015

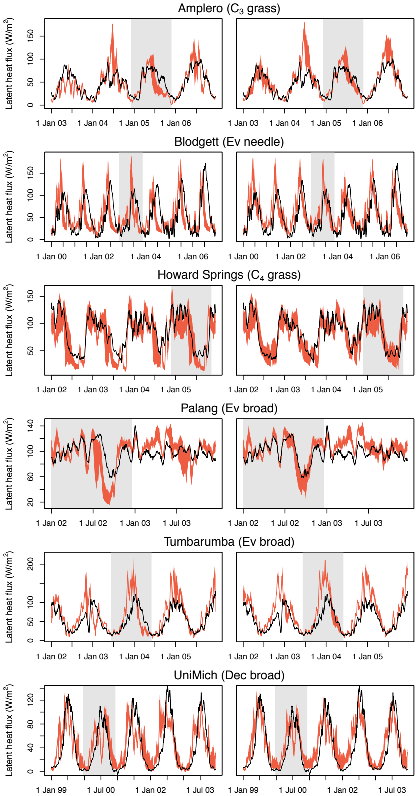

Figure 2. The range in simulated latent heat (red) during the whole observational data period using the default (left panels) and new (right panels) hydrological schemes with alternative LAI, g_s and soil parameterisations. Observed latent heat is shown in black. The grey shading denotes the selected one-year period.

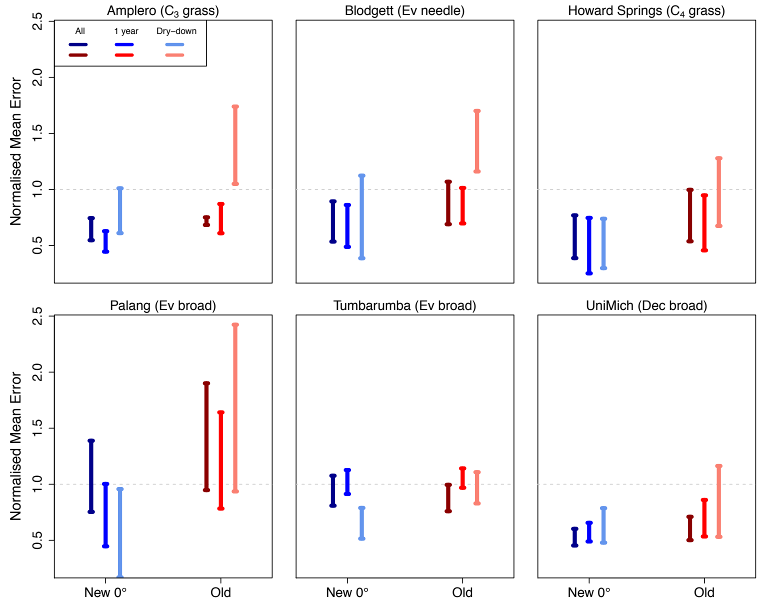

Figure 3. The range in normalised mean error metrics of latent heat simulations using the default (red) and new (blue) hydrological schemes with alternative LAI, g_s and soil parameterisations during the whole, annual and dry-down periods. Values closer to 0.0 indicate better model performance.

HESSD

12, 10789–10825, 2015

Modelling evapotranspiration during precipitation deficits

A. M. Ukkola et al.

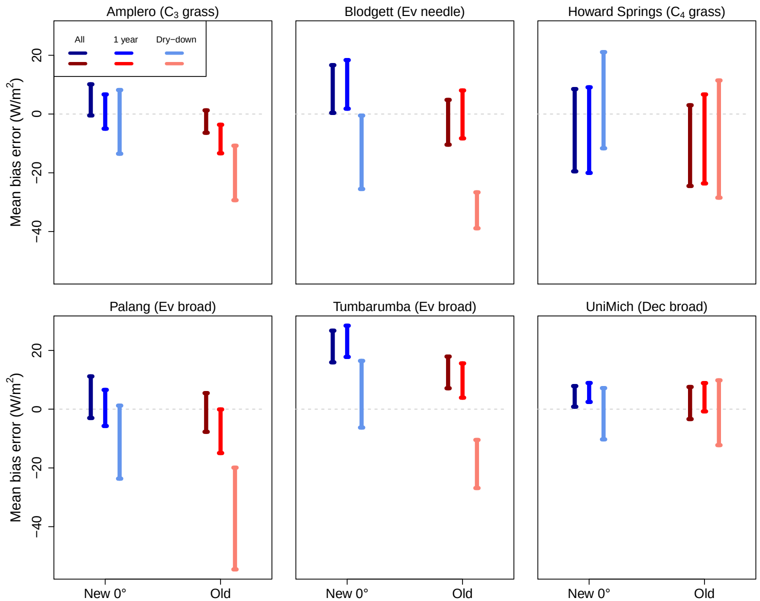

Figure 4. The range in mean bias error metrics of latent heat simulations using the default (red) and new (blue) hydrological schemes with alternative LAI, g_s and soil parameterisations during the whole, annual and dry-down periods. Values closer to 0.0 indicate better model performance.

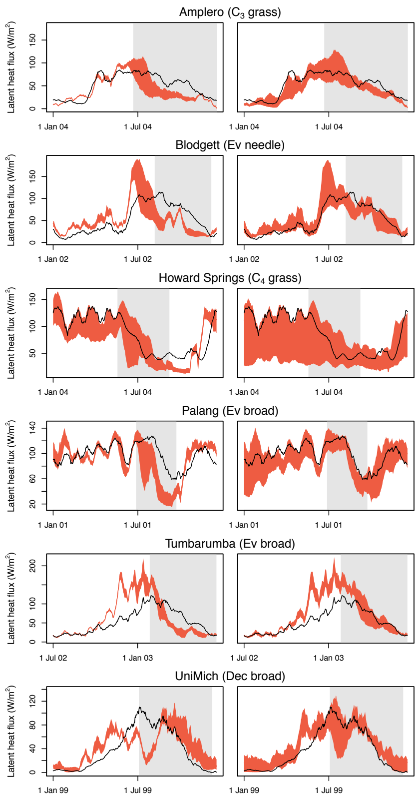

Figure 5. The range in simulated latent heat (red) during the one-year period using the default (left panels) and new (right panels) hydrological schemes with alternative LAI, g_s and soil parameterisations. Observed latent heat is shown in black. The grey shading denotes the selected dry-down period. All time series run from January to December, except Tumbarumba which run from July to the following June.

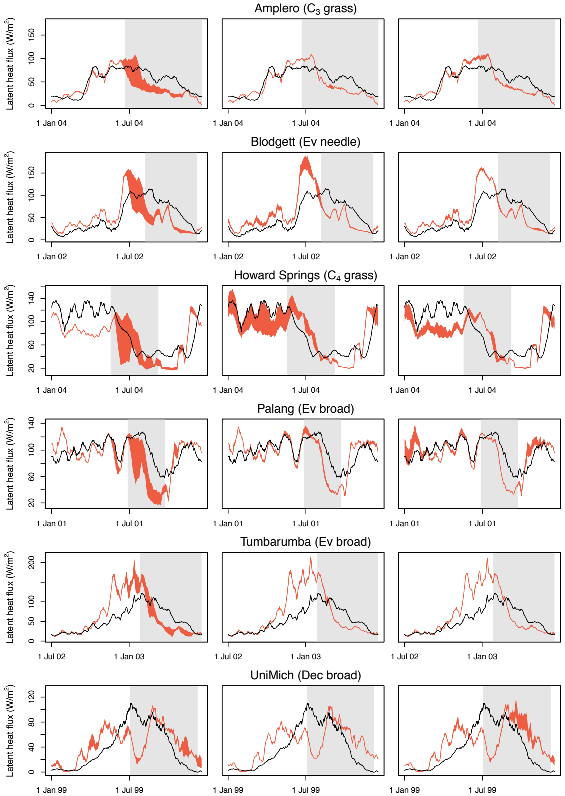

Figure 6. The range in simulated latent heat (red) arising from the individual effects of soil parameters (left panels), g_s (centre panels) and LAI (right panels) using the default hydrological scheme during the one-year period. Observed latent heat is shown in black. The grey shading denotes the selected dry-down period. The individual effects were determined by fixing the other parameterisations at their default values (medium soil, Medlyn g_s and centre LAI).

HESSD
12, 10789–10825, 2015

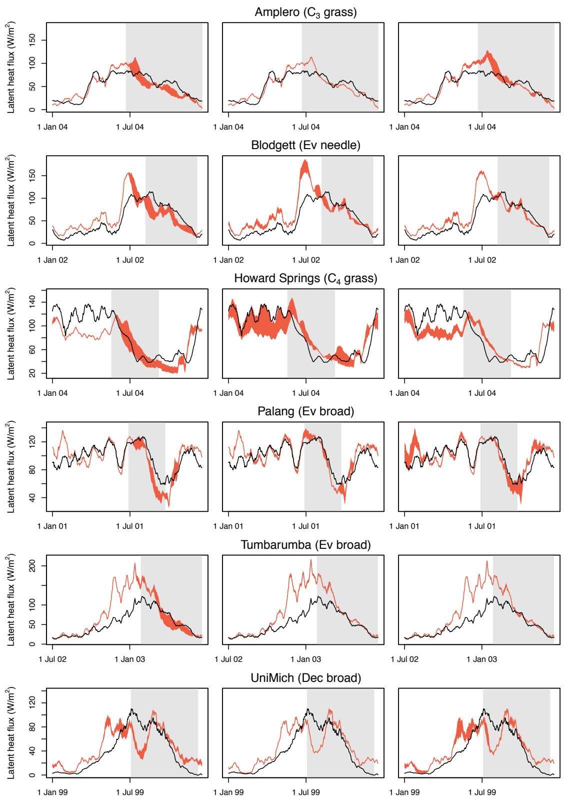

Figure 7. The range in simulated latent heat (red) arising from the individual effects of soil parameters (left panels), g_s (centre panels) and LAI (right panels) using the new hydrological scheme during the one-year period. Observed latent heat is shown in black. The grey shading denotes the selected dry-down period. The individual effects were determined by fixing the other parameterisations at their default values (medium soil, Medlyn g_s, centre LAI and 0° slope).

HESSD
12, 10789–10825, 2015

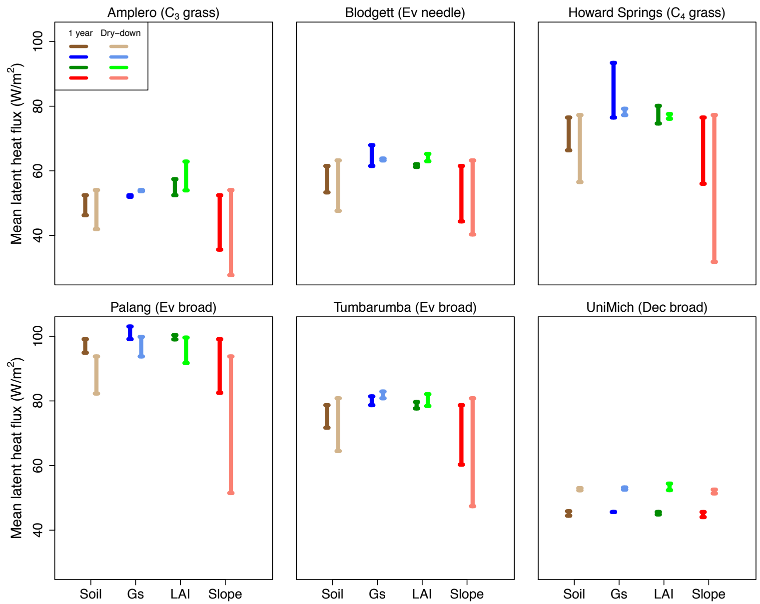

Figure 8. The range in simulated mean latent heat arising from the individual effects of LAI, g_s, soil and slope parameterisations using the default hydrological scheme during the one-year and dry-down periods. The individual effects were determined by fixing the other parameterisations at their default values (medium soil, Medlyn g_s, centre LAI and 0° slope).

HESSD
12, 10789–10825, 2015

Modelling evapotranspiration during precipitation deficits

A. M. Ukkola et al.

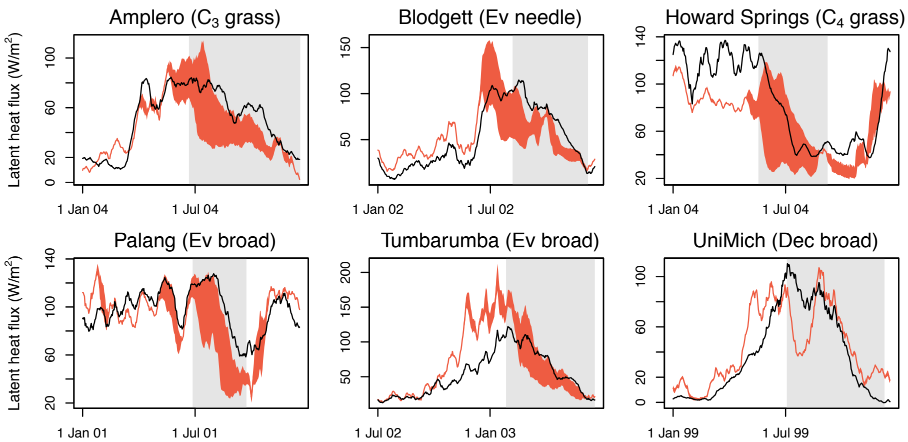

Figure 9. The range in simulated latent heat (red) arising from the individual effects of the slope parameter using the new hydrological scheme during the one-year period. Observed latent heat is shown in black. The grey shading denotes the selected dry-down period. The individual effects were determined by fixing the other parameterisations at their default values (medium soil, Medlyn g_s and centre LAI).

HESSD
12, 10789–10825, 2015