Geosci. Model Dev. Discuss., 8, 5235–5264, 2015 www.geosci-model-dev-discuss.net/8/5235/2015/ doi:10.5194/gmdd-8-5235-2015 © Author(s) 2015. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Geoscientific Model Development (GMD). Please refer to the corresponding final paper in GMD if available.

# Implementation of an optimal stomatal conductance model in the Australian Community Climate Earth Systems Simulator (ACCESS1.3b)

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Received: 19 May 2015 - Accepted: 16 June 2015 - Published: 03 July 2015

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



# Abstract

We implement a new stomatal conductance model, based on the optimality approach, within the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model. Coupled land-atmosphere simulations are then performed using CABLE within

- the Australian Community Climate and Earth Systems Simulator (ACCESS) with prescribed sea surface temperatures. As in most land surface models, the default stomatal conductance scheme only accounts for differences in model parameters in relation to the photosynthetic pathway, but not in relation to plant functional types. The new scheme allows model parameters to vary by plant functional type, based on a global
- <sup>10</sup> synthesis of observations of stomatal conductance under different climate regimes over a wide range of species. We show that the new scheme reduces the latent heat flux from the land surface over the boreal forests during the Northern Hemisphere summer by 0.5 to 1.0 mm day<sup>-1</sup>. This leads to warmer daily maximum and minimum temperatures by up to 1.0 °C and warmer extreme maximum temperatures by up to 1.5 °C.
- <sup>15</sup> These changes generally improve the climate model's climatology and improve existing biases by 10–20%. The change in the surface energy balance also affects net primary productivity and the terrestrial carbon balance. We conclude that the improvements in the global climate model which result from the new stomatal scheme, constrained by a global synthesis of experimental data, provide a valuable advance in the long-term development of the ACCESS modelling system.
  - 1 Introduction

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Stomata control the exchange of water vapour and carbon between the vegetation and the atmosphere. The coupling of the energy, water and carbon exchange at the leaf-level was a profoundly important step in the development of land surface models (LSMs, Sellers et al., 1996). Accurately capturing these exchange processes in LSMs is critical since they affect the terrestrial water, energy and carbon balances (Pit-



man, 2003). Early studies at the point scale have illustrated the potential impact of stomatal behaviour on local meteorology (e.g., Jacobs and De Bruin, 1992; Raupach, 1998; Huntingford and Monteith, 1998). This has prompted a number of investigations showing impacts at both the global (e.g., Henderson-Sellers et al., 1995; Pollard and

- <sup>5</sup> Thompson, 1995) and regional (e.g., Avissar and Pielke, 1991; Martin et al., 1999; Cruz et al., 2010) scales. Recent studies have also shown that the different physiological response of tropical forests to increasing CO<sub>2</sub> is a larger source of uncertainly in estimating future Carbon stocks than the future emission scenarios (Huntingford et al., 2013). Similarly, other studies suggest that physiological adaptations of subtropical vegetation
- to increasing  $CO_2$  could account for reductions in the annual transpiration flux of up to ~ 60 W m<sup>-2</sup> in some regions (de Boer et al., 2011). Given such large impacts, there is currently an urgent need to explore accurate representations of stomatal behaviour suitable for implementation in LSMs within general climate models (Huntingford et al., 2015).
- <sup>15</sup> It is common in LSMs (e.g., Sellers et al., 1992; Bonan, 1995; Cox et al., 1998; Wang et al., 2011) to represent stomatal conductance ( $g_s$ ) using an empirical model (Jarvis, 1976; Ball et al., 1987; Leuning, 1995). Whilst parameters for these empirical models can easily be calibrated using experimental data, in practice they rarely are. Instead, the current suite of LSMs, including the Community Atmosphere Biosphere Land
- Exchange (CABLE, Wang et al., 2011), only differentiate model parameters by photosynthetic pathway (C3 vs. C4) (Krinner et al., 2005; Oleson et al., 2013), rather than by plant functional type (PFT). Medlyn et al. (2011) proposed an alternative approach, deriving a stomatal conductance scheme from optimal stomatal theory. This approach maintains the same functional form as the empirical models, but attaches a theoreti-
- <sup>25</sup> cal meaning to the model parameters. Parameters now represent a plant's water use strategy and thus can be hypothesised to vary across climate space. Lin et al. (2015) used a global database of  $g_s$  data to show that stomatal behaviour varied between PFTs as predicted by the optimal stomatal theory (and the leaf and wood economic spectrum), in line with the Medlyn et al. (2011) model. De Kauwe et al. (2015) tested



an implementation of this  $g_s$  scheme within CABLE using flux tower observations and global offline forcing and showed a ~ 30 % reduction in annual fluxes of transpiration compared to the standard CABLE model across boreal, tundra and C4 grass regions.

This paper extends De Kauwe et al. (2015) in several ways. CABLE is the LSM used

- <sup>5</sup> in the Australian Climate and Earth Systems Simulator (ACCESS) (Bi et al., 2013), a global climate model that performed very well in comparison with observations within the Coupled Model Intercomparison Project (CMIP-5, Flato et al., 2013). Our first goal is to test the feasibility of using the De Kauwe et al. (2015) implementation of the Medlyn et al. (2011) stomatal conductance scheme globally, within the ACCESS cou-
- <sup>10</sup> pled land-atmosphere climate model. De Kauwe et al. (2015) showed that the new scheme generally improved CABLE's performance in off-line experiments, forced by prescribed meteorology and evaluated using observations. Our second goal is to determine whether this improved performance is sustained in the coupled environment of the ACCESS model. ACCESS has a satisfactory control climate in terms of means
- (Bi et al., 2013; Kowalczyk et al., 2013), but Lorenz et al. (2014) examined the model's climatology in terms of some extremes linked with the land surface and showed serious problems in the simulation of the diurnal temperature range due to biases in both maximum and minimum temperatures. We seek to determine whether these problems, affecting these and other extreme indices can be resolved in part via the parameteri-
- <sup>20</sup> zation of  $g_s$ . We also note that ACCESS is also used for numerical weather prediction (NWP) in Australia (Puri et al., 2013) and hence our results have implications for modelling across time scales.

#### 2 Methods

# 2.1 Model description

<sup>25</sup> We use the Australian Community Climate Earth System Simulator version 1.3b (AC-CESS1.3b). The set-up follows Lorenz et al. (2014) and consists of the atmospheric



Unified Model (UM7.3) (Davies et al., 2005; Martin et al., 2006), CABLE2.0, the Modular Ocean Model, and a coupling framework that couples the ocean and sea ice to the atmosphere (Bi et al., 2013). We use ACCESS1.3b in an Atmospheric Model Intercomparison Project (Gates, 1992, AMIP) configuration with prescribed sea surface
temperatures and sea ice fractions. These were sourced from the Program for Climate Model Diagnosis and Comparison (Taylor et al., 2000) and re-gridded and converted to the Unified Model data format. We performed simulations at 1.25° latitude by 1.875° longitude resolution (N96 resolution), with 38 vertical levels, and a 30 min time step. Further details of the ACCESS model can be found in Bi et al. (2013) and Lorenz et al. (2014).

## 2.2 New stomatal conductance scheme

The implementation of the new  $g_s$  scheme was documented by De Kauwe et al. (2015), and we only provide a brief description here. The default  $g_s$  (mol m<sup>-2</sup> s<sup>-1</sup>) scheme in CABLE is based on Leuning (1995):

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$$g_{s} = g_{0} + \frac{a_{1}\beta A}{(C_{s} - \Gamma)\left(1 + \frac{D}{D_{0}}\right)}$$
 (1)

where *A* is the net assimilation rate ( $\mu$ mol m<sup>-2</sup> s<sup>-1</sup>), *C*<sub>s</sub> ( $\mu$ mol mol<sup>-1</sup>) and *D* (kPa) are the CO<sub>2</sub> concentration and the vapour pressure deficit at the leaf surface respectively,  $\Gamma$  ( $\mu$ mol mol<sup>-1</sup>) is the CO<sub>2</sub> compensation point of photosynthesis, and  $g_0$  (mol m<sup>-2</sup> s<sup>-1</sup>),  $D_0$  (kPa) and  $a_1$  are fitted constants representing the residual stomatal conductance as the assimilation rate reaches zero, the sensitivity of stomatal conductance to D, and the sensitivity of stomatal conductance to assimilation, respectively. In CABLE, the fitted parameters  $g_0$  and  $a_1$  vary with photosynthetic pathway (C3 vs. C4) but not PFT, and  $D_0$  is fixed for all PFTs.  $g_0$  is scaled from the leaf to the canopy by accounting for leaf area index, following Wang and Leuning (1998).  $\beta$  represents an empirical soil



moisture stress factor:

$$\beta = \frac{\theta - \theta_{\rm w}}{\theta_{\rm fc} - \theta_{\rm w}}; \beta[0, 1]$$

where  $\theta$  is the mean volumetric soil moisture content (m<sup>3</sup> m<sup>-3</sup>) in the root zone,  $\theta_w$  is the wilting point (m<sup>3</sup> m<sup>-3</sup>) and  $\theta_{fc}$  is the field capacity (m<sup>3</sup> m<sup>-3</sup>).

In this study we replaced Eq. (1) with the  $g_s$  model of Medlyn et al. (2011) and the same  $\beta$  factor as above:

$$g_{\rm s} = g_0 + 1.6 \left(1 + \frac{g_1 \beta}{\sqrt{D}}\right) \frac{A}{C_{\rm s}}$$

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where  $g_1$  (kPa<sup>0.5</sup>) is a fitted parameter representing the sensitivity of the conductance to the assimilation rate. In this formulation of the  $g_s$  model, the  $g_1$  parameter has a theoretical meaning:

$$g_1 \propto \sqrt{\frac{\Gamma^*}{\lambda}}$$

where  $\lambda$  (mol C mol<sup>-1</sup> H<sub>2</sub>O) is the marginal carbon cost of water use and  $\Gamma^*$  (µmol mol<sup>-1</sup>) is the CO<sub>2</sub> compensation point in the absence of mitochondrial respiration. As a result,  $g_1$  is inversely related to the marginal carbon cost of water (Medlyn et al., 2011).

Values of  $g_1$  for the CABLE PFTs (Fig. 1) are shown in Table 1. These have been compiled from a global database of stomatal conductance from 314 species across 56 field sites (Lin et al., 2015) including Arctic tundra, boreal, temperate forests and tropical rainforest biomes. Further details can be found in De Kauwe et al. (2015).

#### 2.3 Simulations

<sup>20</sup> Two sets of simulations were carried out, the control simulation using the default Leuning (1995) scheme (LEU, Eq. 1) and the experiment using the Medlyn et al. (2011)



(2)

(3)

(4)

scheme (MED, Eq. 3). ACCESS1.3b simulations cover the period 1950–2012. The first 10 years were used as a spin-up period and are not included in the analysis. Five ensembles were carried out for each simulation, initialized a year apart, so that the impact of natural model variability is reduced and any signal from the change in  $g_s$  is clear rel-<sup>5</sup> ative to internal model noise. Results are shown averaged over these 5 ensembles.

The initial conditions are the same as those used by Lorenz et al. (2014).

We note that CABLE has the ability to incorporate carbon pool dynamics with nitrogen and phosphorus limitations and simulate leaf area index (LAI) (Wang et al., 2010), i.e., dynamic phenology can be activated. This feature was not used here. Instead, sim-

<sup>10</sup> ilar to the experimental set-up of Lorenz et al. (2014), a monthly climatology derived from MODIS estimates was used. This was deliberate so as to allow comparisons with Lorenz et al. (2014) and additionally, as a first step, it is critical to first isolate the biophysical effects of the new  $g_s$  scheme before considering the combined biophysical and biogeochemical effects.

#### 15 2.4 Benchmarking datasets

We use a similar benchmarking data-sets to those employed by Lorenz et al. (2014) in a prior evaluation of the ACCESS1.3b climatology of both mean and extremes of temperature and precipitation.

Maximum ( $T_{MAX}$ ) and minimum ( $T_{MIN}$ ) temperatures were obtained from the HadGHCND gridded daily temperature data set (Caesar et al., 2006), which is derived from near-surface maximum and minimum temperature observations from 1951 to present at a 2.75° latitude by 3.75° longitude resolution. We also used the Expert Team on Climate Change Detection and Indices (ETCCDI, http://www.climdex. org/indices.html), which are derived from daily  $T_{MAX}$  and  $T_{MIN}$ . The indices chosen for this study include the warmest seasonal maximum (TXx) and the di-urnal temperature range (DTR, the amplitude between  $T_{MAX}$  and  $T_{MIN}$ ). These indices are from the HadEX2 dataset and described in detail by Donat et al. (2013). These indices were



over-estimation of  $T_{\rm MIN}$ , leading to an under-estimation of the DTR. The ACCESS results were interpolated to the HadGHCND domain prior to comparison as they are at a higher resolution. Seasonal means of  $T_{\rm MAX}$ ,  $T_{\rm MIN}$ , DTR and TXx were computed over the period 1960–2010.

We also tested the influence of the new scheme on precipitation using the Global Precipitation Climatology Project (GPCP) dataset version 2 (http://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html). This data-set is derived from a combination of satellite and rain-gauge measurements and is available at a 2.5° latitude by 2.5° longitude resolution. The ACCESS precipitation was interpolated to the GPCP grid and seasonal
 means were computed over the period 1979–2011.

Finally, given the influence of  $g_s$  on the exchange of water vapour from vegetation to the atmosphere, we assess the influence of the new scheme on total evapotranspiration (ET). While there are no direct observations of ET available at the global scale, the LandFlux-EVAL data set (Mueller et al., 2013) provides a comprehensive ensemble of global ET estimates at a 1° latitude by 1° longitude resolution, derived from

<sup>15</sup> ble of global ET estimates at a 1° latitude by 1° longitude resolution, derived from various satellites, LSMs driven with observationally based forcing, and atmospheric reanalysis. We used data over the period 1989 to 2005 and the LandFlux ET product was interpolated to the ACCESS domain as it is at a higher resolution.

For all comparisons of ACCESS against the various datasets, seasonal means were computed from each of the 5 ensembles separately, then averaged for comparison.

## 3 Results

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Figure 2 shows the seasonal mean differences in  $T_{MAX}$  during the Boreal winter (December–January–February, DJF) and summer (June–July–August, JJA) between the MED and LEU simulations and observations over the period 1960 to 2010 (panels a to d), as well as the differences between the MED and LEU simulations (panels e to f). All results are averaged across the 5 ensembles. The two climatologies from the ACCESS1.3b model are very similar, and show similar large-scale biases. There are,



for example, large biases over the Himalayas and parts of North America during DJF and JJA, as well as Australia and South America in JJA, irrespective of whether MED or LEU is used. Unsurprisingly, to first order, the parameterization of  $g_s$  does not resolve the large-scale biases in ACCESS1.3b. The differences between the two experiments (MED-LEU) however demonstrate an improvement in the  $T_{MAX}$  bias over the Boreal

- forests in JJA of up to 1 °C, but the positive bias over North America is increased. MED also leads to warming, relative to LEU, of ~ 0.3 °C over the regions of tropical forest over South America and Africa. A large region of Eurasia warms with MED in DJF by ~ 0.3 °C, reducing the bias in ACCESS1.3b. Figure 3 shows the same results but for
- <sup>10</sup>  $T_{\rm MIN}$  and the results are broadly similar to the  $T_{\rm MAX}$  results. Specifically, the inherent biases within ACCESS1.3b remain and the net effect of the MED  $g_{\rm s}$  scheme is a small overall increase in the biases associated with  $T_{\rm MIN}$ . However, the simulation of  $T_{\rm MIN}$  is worsened in some regions, particularly in JJA over North America, likely linked with poor simulations of cloud (Franklin et al., 2013).
- <sup>15</sup> Having examined the influence of the new  $g_s$  scheme on  $T_{MAX}$  and  $T_{MIN}$ , we now focus on two extreme temperature indices based on  $T_{MAX}$  and  $T_{MIN}$ , namely, the warmest  $T_{MAX}$  of the year (TXx, Fig. 4) and DTR (Fig. 5). ACCESS1.3b has a systematic cold bias in TXx in both DJF (Fig. 4c) and JJA (Fig. 4d) using LEU. In both seasons, this cold bias commonly exceeds 10 °C. Replacing LEU with MED reduces this cold bias by up
- to 20 % over Eurasia and parts of North America. The MED-LEU difference (Fig. 4e, f) is almost always positive, implying a reduced error over most of the globe using MED. Remarkably, a large region of warm bias to the north east of the Mediterranean cools with MED relative to LEU in JJA (Fig. 4f) reducing this bias by ~ 20 %. While clearly not resolving all biases in TXx, replacing LEU with MED clearly leads to improvements
- <sup>25</sup> and has a regional impact that helps reduce both positive and negative biases in the model.

One of the errors identified by Lorenz et al. (2014) was an unsatisfactory simulation of the diurnal temperature range (DTR). Figure 5 shows little impact by switching to MED in DJF, but in JJA there are large areas of the Northern Hemisphere, coincident



with the boreal forests, where the 3–5 °C error in DTR is reduced by 10–20 %. Clearly, using MED does not resolve ACCESS's limitations in capturing the observed DTR, but the magnitude of the error is reduced.

The change in the  $q_s$  parameterization has the most immediate effect on vegetation <sup>5</sup> transpiration (here represented as part of the total moisture flux, evapotranspiration, ET). Figure 6 shows comparisons between the two experiments and the LandFlux ET as well as the differences between the two simulations. There are two major regions where MED leads to reduced ET. Over the boreal forests, ET is reduced by  $\sim 0.1 0.3 \,\mathrm{mm}\,\mathrm{day}^{-1}$  which reduces the high ET bias seen in LEU (Fig. 6c, d). MED also reduces ET in the tropical forest regions by  $\sim 0.1 \,\mathrm{mm \, day^{-1}}$  again generally reducing the bias seen in LEU. There are regions where the use of MED degrades the simulation (relative to the LandFlux product), for example over eastern Australia in DJF and through the croplands of western and Eastern Europe.

The changes in ET directly affect total precipitation (Fig. 7). In DJF, ACCESS1.3b has a wet bias over Amazonia and southern Africa and these biases are reduced using 15 MED. In JJA ACCESS1.3b has a wet bias over the boreal forests and a dry bias over the region to the north west of the Mediterranean. Replacing LEU with MED reduces this wet bias over the boreal forests by  $\sim 10\%$  but does not resolve the bias to the north west of the Mediterranean. A wet bias in JJA is also reduced (Fig. 7h) in areas of the tropics. Further to affecting elements of the hydrological cycle through precipitation, the 20

- reduced ET also affects the terrestrial carbon balance via the net primary productivity (NPP, Fig. 8). There is a clear reduction in NPP coincident with the Boreal Forests in JJA (Fig. 8b) and in the tropics in both JJA and DJF (Fig. 8). There is also an increase in NPP in JJA in the region to the north and east of the Mediterranean, consistent with
- an increase in ET in this region (Fig. 6h) using MED. 25



## 4 Discussion

We implemented a new  $g_s$  scheme within the ACCESS global climate model by modifying the CABLE LSM. The new scheme, MED, has advantages over the LEU scheme in being founded on optimization theory and utilizing a database of stomatal conductance data (Lin et al., 2015) with a reasonable, if heterogeneous, spatial coverage. The MED  $g_s$  scheme also has an advantage that it improves the performance of CABLE's simulation of ET in off-line studies, particularly for boreal forests, against a wide range of flux station observations as well as global offline simulations forced by re-analysis (De Kauwe et al., 2015). One aim of this paper was to determine if the MED  $g_s$  scheme would show similar improvements within the ACCESS1.3b climate model.

An advantage of using an analytical model based on optimization theory rather than an empirical model is that it provides a foundation for future model parameterization development. Our implementation of the optimal model has one key parameter,  $g_1$ , which is related to the marginal carbon cost of water. It is qualitatively possible to use

- theoretical considerations to predict how this parameter should vary among PFTs and with mean annual climate (e.g., Prentice et al., 2014; Lin et al., 2015). For example, Lin et al. (2015) demonstrated a significant relationship ( $r^2 = 0.89$ ) between  $g_1$  and two long-term average (1960–1990) bioclimatic variables: temperature and a moisture index representing an indirect estimate of plant water availability. This implies
- that links between changing temperature and moisture could, in principle, be built into MED (De Kauwe et al., 2015). For example, in the future, there is the potential to build a framework that enables ecophysiology research utilizing flux tower observations to be more strongly coupled with global climate modelling via the use of parameterization schemes which are more founded in observations. There is considerable likelihood
- that  $g_s$  schemes built on new theory and informed by observations would affect how the terrestrial carbon balance responded to climate change and the direct forcing by increased atmospheric CO<sub>2</sub>.



Our results show first and foremost, that replacing LEU with MED results in an overall decrease in ET by 0.1 to  $0.3 \,\text{mm}\,\text{day}^{-1}$  and subsequent warming signal of up to  $1\,^\circ\text{C}$ , mostly over the boreal forests. However, this does not drastically change the overall climatology of ACCESS at the global scale. Modelling groups using parameterizations

- <sup>5</sup> based on approaches similar to LEU are unlikely to result in major errors. However, at regional scales, in particular in the Boreal Forests and to a lesser degree in the tropical forests using MED in ACCESS does reduce systematic model biases in  $T_{MAX}$ , in other warm extremes and in rainfall. It is noteworthy that the largest improvements are in the most extreme metrics used for temperature, suggesting that while MED may not make
- <sup>10</sup> a major impact on the mean temperature, it does affect  $T_{MAX}$  and  $T_{MIN}$ , and affects TXx quite strongly. We plan to examine the impact of using MED in the simulation of present and future temperature extremes in forthcoming work.

Replacing LEU with MED reduces ET (Fig. 6) in the boreal forests and to a lesser degree in the tropics. These changes are of a similar order of magnitude, but generally

- <sup>15</sup> smaller, as those reported by De Kauwe et al. (2015) in their off-line simulations with the MED  $g_s$  in CABLE. This reduction in ET results from the lower  $g_1$  used in this region which reflects a more conservative water use strategy of the vegetation (Lin et al., 2015) and the resulting lower  $g_s$  reduces ET. This reduction in ET varies between vegetation types and in CABLE there tends to be a stronger impact on boreal regions
- (coniferous evergreen forest) in comparison to grasslands and crops. All subsequent results are a direct consequence of this first order impact in ET. The reduction in ET reduces the latent heat flux and by energy balance constraints, increases the sensible heat flux. This modification to the surface energy balance leads to surface warming. Since this tends to be amplified during the day when net radiation is higher we see
- <sup>25</sup> a stronger impact on  $T_{MAX}$  than  $T_{MIN}$ , and since the impact of reduced latent heat can have a proportionally stronger impact on temperature extremes we see a larger impact on TXx. The lower latent heat flux means a lower moisture flux into the atmosphere, which tends to reduce precipitation. The lower ET also reduces the capacity of the vegetation to fix carbon and tends to lead to a lower net primary productivity.



It is worth commenting on why the change in ET (Fig. 6) is generally smaller in our coupled experiments in comparison to the off-line results reported by De Kauwe et al. (2015). Coupling a LSM to an atmosphere introduces feedbacks; a change in ET can impact rainfall as found in our results, but it can also impact cloud cover, incoming solar radiation and thereby net radiation. These feedbacks are complex and examining the relative contributions of each component requires an explicit experimental design and the storage of variables that we did not attempt here because it was beyond the scope of our study. It would be useful, in the future, to examine how the change in conductance directly affects ET in contrast to how it triggers feedbacks that indirectly affect ET.

We note that the differences shown here between LEU and MED predominately result from the new spatial varying  $g_1$  parameter values (Fig. 1 and Table 1), rather that the different structures of the  $g_s$  models (Eqs. 1 and 3). De Kauwe et al. (2015) used offline global simulations to investigate the relative roles of structure vs. parameter-

- <sup>15</sup> isation, concluding that structure only resulted in small differences in ET estimates. We also note that a limitation of our work is that we use a prescribed LAI climatology, however, this is not uncommon in global climate models. It is highly likely that the use of prognostic LAI would result in larger differences between the two schemes and this will be subject to future work. For example Piao et al. (2006) have shown using
- <sup>20</sup> a global dynamic vegetation model that changes in climate and ambient CO<sub>2</sub> strongly influence greening trends in the Northern Hemisphere (> 25° N). Our use of a prescribed monthly LAI climatology does not allow for such feedbacks, and additionally, MODIS LAI has known inaccuracies over forested regions (e.g., Shabanov et al., 2005; De Kauwe et al., 2011; Sea et al., 2011; Serbin et al., 2013).
- Finally, we note that other land surface modelling groups are also moving towards replacing empirical scheme of  $g_s$  with schemes that explicitly account for optimal behaviour. For example, Bonan et al. (2014) replaced the original empirical stomatal conductance model (Ball et al., 1987) within the Community Land Model with a numerical scheme based on Williams et al. (1996), which optimizes carbon gain per unit of water



loss while also limiting stomatal opening to prevent leaf water potential from dropping below critical levels. This has been shown to improve simulations offline, similar to De Kauwe et al. (2015). Our implementation differs in that we use an analytical solution, and account for soil-water limitation via the empirical scalar relationship in Eq. (2), rather than solve for it numerically. Nonetheless, the the  $g_s$  model presented here can be extended to other LSMs both offline and coupled, but would require a subjective mapping of  $g_1$  to PFT classifications used by different LSM groups.

## 5 Conclusions

We had three goals for this paper. First, we sought to test the feasibility of using the Medlyn et al. (2011) stomatal conductance scheme, based on optimal stomatal theory, 10 within the ACCESS global climate model. We have demonstrated that this is feasible. Our second goal was to determine whether the improvements found by using the Medlyn et al. (2011) stomatal conductance scheme in off-line simulations (De Kauwe et al., 2015) was also found in the ACCESS1.3b coupled model. We have shown that by reducing evapotranspiration, temperatures are increased which generally reduces 15 associated biases by around 10–20% over the Boreal forests. Maximum temperatures are generally improved, but major error systematic biases in minimum temperatures remain and are in some cases made worse. This can be expected as ACCESS is known to systematically over predict minimum temperatures, and the net effect of the MED scheme is an overall warming due to a reduction in ET. Lorenz et al. (2014) linked the 20 biases in  $T_{MIN}$  to systematic biases in incoming longwave radiation, and hence we expect that future improvements within ACCESS's atmospheric component will resolve this.

The reduction in evapotranspiration also affects rainfall, generally reducing some regional-scale biases. This also affects net primary productivity, with regions of decrease (increase) in evapotranspiration corresponding to regions of decrease (increase) in net primary production. The majority of these changes are clearly associated



with boreal forest regions, but areas of the tropics and to a lesser degree areas of croplands in Eurasia are also affected. Using the Medlyn et al. (2011) stomatal conductance scheme therefore helps address improve aspects of the ACCESS1.3b model and also helps address some of the extremes biases found by Lorenz et al. (2014). However, while some of the systematic biases are reduced, they were not fully resolved and thus

other major problems must exist in the ACCESS-CABLE system.

The Medlyn et al. (2011) stomatal conductance scheme is founded in ecological theory and it adds skill to our global model and has the potential to be developed further to account for physiological responses to climate change and increasing atmospheric

<sup>10</sup> carbon dioxide. Given these advantages, we plan to use it in CABLE since we expect it provides a framework for longer-term, more flexible, more data informed and more successful future model developments in the long-term than alternative schemes. Future work will focus on the impact of the new scheme on future climate simulations under different representative concentration pathway scenarios.

#### 15 6 Code availability

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The CABLE source code is publicly available upon registration at https://trac.nci. org.au/trac/cable. The modified version of CABLE with the new  $g_s$  scheme can be viewed by registered users at https://trac.nci.org.au/trac/cable/browser/branches/Share/CABLE-2.0.1-Tagged-plus-Medlyn-Stom-Param. The ACCESS model source code is not publicly available, but information can be found at https://accessdev.nci. org.au/trac/wiki/access.

Acknowledgements. This work was supported by the Australian Research Council Centre of Excellence for Climate System Science (CE110001028) and the NSW Environment Trust (RM08603). We thank the National Computational Infrastructure at the Australian National University, an initiative of the Australian Government, for access to supercomputer resources. We thank CSIRO and the Bureau of Meteorology through the Centre for Australian Weather and Climate Research for their support in the use of the CABLE and ACCESS models. The GPCP



combined precipitation data were developed and computed by the NASA/Goddard Space Flight Center's Laboratory for Atmospheres as a contribution to the GEWEX Global Precipitation Climatology Project. GPCP data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from theirWeb site at http://www.esrl.noaa.gov/psd/. This study uses the LandFlux-EVAL

5 merged benchmark synthesis products of ETH Zurich produced under the aegis of the GEWEX and ILEAPS projects (http://www.iac.ethz.ch/groups/seneviratne/research/LandFlux-EVAL). All this assistance is gratefully acknowledged.

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Table 1.	Fitted $g_1$	values	for the	PFTs	shown	in	Fig.	1.
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PFT	g <sub>1</sub> (kPa <sup>0.5</sup> )
Evergreen needleleaf	2.35
Evergreen broadleaf	4.12
Deciduous needleleaf	2.35
Deciduous broadleaf	4.45
Shrub	4.70
C3 grassland	5.25
C4 grassland	1.62
Tundra	2.22
C3 cropland	5.79

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**Figure 2.** (**a**–**d**): mean seasonal difference in maximum temperature ( $T_{MAX}$ ) between the MED and LEU experiments and the HADGHCND dataset (OBS) during boreal summer (JJA, left panels) and winter (DJF, right panels), and (**e**–**f**): difference between the MED and LEU simulations. Seasonal means are computed over the period 1960–2010. Inland areas in white for panels (**a**–**d**) represent missing data.





**Figure 3.** Same as in Fig. 2 except for minimum temperature ( $T_{MIN}$ ).





**Figure 4.** Same as in Fig. 2 except for the warmest maximum (TXx). Observations are from the HADEX2 dataset and seasonal means are computed over the period 1960–2010.











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Interactive Discussion

Figure 6. Same as in Fig. 2 except for evapotranspiration (ET). Multi-model estimates are from the LandFlux (LF) dataset and seasonal means are computed over the period 1989-2005.









Figure 8. Mean seasonal difference in net primary productivity between the MED and LEU simulations.

