We thank the reviewers for their thoughtful comments that have improved the revised version of this manuscript. We have made several changes to address the concerns that were raised, including:

1) *Emphasizing the large uncertainty in observed and modeled daytime minimum conductance*
2) *Further clarifying that all our implementations adjust the minimum conductance value based on soil moisture stress, since adjusting for VPD is not practical using currently available data*
3) *Improving the description of the different methodologies to observational data.*
4) *Adding more detail to the methods to clarify how the data were collated, highlighting our tests of alternative methods and estimates of error in the supplementary information.*
5) *We updated the title to include the model version and number, and include a "Code and Data Availability" section with instructions for how to acquire the model code and the observed nighttime stomatal conductance data*

Please find the detailed response to each reviewer's comments included in italics below.

Comments from Josh Fisher

The motivation behind this study is excellent—recent empirical measurements have discovered a robust and interesting dynamic whereby plants can lose water at night. This has transformed our understanding of plant physiology coupled to the atmosphere. When such transformation of understanding occurs, models of these dynamics should also be updated, and this is what this study intends to do; and, in an important model—CLM—which has overly-simplified stomatal conductance parameterizations well-structured for updating.

I would have thought this study would be relatively straightforward, and I expected to review the paper without much comment, giving my stamp of approval for a good model update. However, there are potentially very serious critical flaws in the approach. This is evident in the methods and manifest in the shocking results (50% reduction in semi-arid soil moisture seems way too high and is rather questionable, given that nighttime transpiration in semi-arid regions should not be 50% of total daily transpiration—is this even physically possible, or is this substantiated by observations?). The authors equate nighttime conductance/transpiration with minimum conductance/transpiration (this is the fundamental change they implement). However, these are not the same thing. Nighttime transpiration does not occur all the time in the empirical literature within plants that it can occur. The minimum conductance can easily be 0, but when conditions are ripe—high VPD, etc.—nighttime transpiration kicks in. So, this could be a fatal flaw.

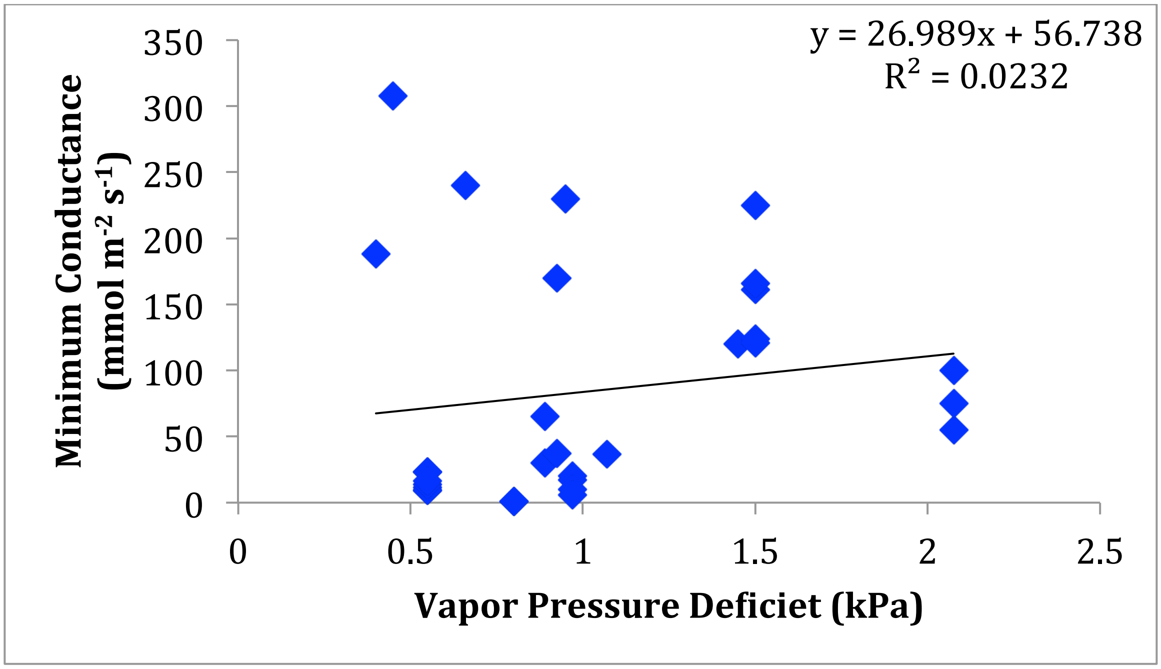
***Author Response**: Thanks for highlighting the need to communicate the model modifications used here more effectively. As you appreciate already, our basic premise* *is that observed nighttime stomatal conductance is observed to be substantially higher than the default value used in the CLM (see SI Table 1). In particular, observations of nighttime conductance in semi-arid and desert ecosystems show that these ecosystems can have quite high nighttime conductances. For example, Ogle et al. 2012 measured day and night conductance in desert plants, and found that nighttime stomatal conductance was 43-71% of daytime conductance in shrubs, and 35-49% of daytime in C_4 grasses. It was not out intention to conflate stomatal conductance with transpiration – we altered only the formulation of stomatal conductance in the model, and only used data on stomatal conductance values from the literature, not transpiration. In the CLM, transpiration is calculated using both stomatal conductance and prevailing canopy humidity to calculate transpiration, hence, the control of VPD should be an emergent property of the model (as illustrated by the strength of the impact in places with a high nighttime VPD) rather than an input.*

What should have been done is to make g0 a function of environmental variables (e.g., VPD) so that it can vary between 0 (or 10 or whatever baseline) and the observed gs,n data. This could probably help out the shocking semi-arid soil moisture 50% reduction results because VPD would probably be high only when the soil moisture was low anyway, so there wouldn't be much absolute loss. The authors kind of hint at this in Section 3 (which, noted, I enjoyed reading, though perhaps should have been part of the Introduction given that the authors are questioning themselves in it).

We would indeed like to consider the potential impact of additional environmental controls on nighttime g_s, particularly given that there is limited understanding of its physiological role. Anecdotally, Ogle et al. 2012 find that C_4 grass nighttime g_s was sensitive to nighttime VPD, while C_3 shrubs were not, and Cavender-Bares et al. (2007) found that nighttime transpiration in drought-treated plants did not respond to nighttime VPD. Therefore, we interrogated our dataset to find out whether this relationship exists and if it can defensibly be integrated into the CLM.

*In our compiled data (SI Table 1), we find that there is no correlation between nighttime conductance and VPD (see figure below). It is therefore unclear how we would generate a parameterization to adjust the minimum threshold value based on VPD that could be generalized across space and through time. For comparison, g_o in the unmodified BWB formulation is not typically adjusted for VPD, either. In the default CLM, however, the soil moisture stress scalar **does** impact the minimum conductance value, g_o, and we similarly expand that function so that the soil moisture stress scalar adjusts the minimum threshold value we use (Table 2) based on nighttime conductance observations. It is expected that this mechanism should move nighttime water loss closer to zero during periods of intense moisture stress (see lines 124-127 in section 2.1).*

It is also important to note that our figures show percent changes for the various *methods we implemented, which can be quite high even if absolute changes are small (noted in lines 289-290). To showcase this, we present the absolute values from the control simulation (i.e., unmodified BWB model), and then the percent changes caused by each modification. For example, Fig 2a illustrates the absolute value of transpiration in the control simulation, while Figs. 2b and 2c show the percent change in transpiration from the control. The regions with large (~50%) changes are primarily regions that transpire <100 mm* H_2O *per year (e.g., compare Fig. 2a to Fig. 2c).*



I also note that the authors seem to be missing a large piece of the empirical literature on nighttime transpiration, particularly from sap flow. Much of this was synthesized in a *Tree Physiology* special issue in 2007, and there have been many other papers since then using the technique for this analysis. These papers describe the environmental sensitivities of nocturnal transpiration, e.g., the mechanistic basis for updating the models as I suggested above.

Author Response*: Supplemental Table 1 compiles all available nighttime conductance data using gas exchange and sap flow techniques. The CLM4.5 predicts transpiration based on stomatal conductance, so we only use data where nighttime stomatal conductance is reported, and do not use data where nighttime transpiration is reported. We do include values from the* Tree Physiology *2007 special issue, but only include values that can be used in our model parameterization. Additionally, the papers in that special issue do include environmental sensitivities of nighttime conductance, but most studies found that some plant types were sensitive to these environmental factors, while others were not (please see points above for further discussion).*

Specific comments:

- Title: slightly awkward wording—it's not that observations cause an alteration of models.

Author Response*: We updated the title to "Incorporating observed nighttime conductance alters global hydrology and carbon budgets in CLM4.5"*

- Title: I think that GMD has changed their policy and wants all papers to have model names and version numbers in the titles (e.g., CLM4.5SP).

Author Response*: We updated the title to "Incorporating observed nighttime conductance alters global hydrology and carbon budgets in CLM4.5" to include the model and version number.*

- Abstract: here it would definitely be worth mentioning which land surface model.

Author Response*: We now include that we use the CLM4.5 (Abstract, line 25): "Here, we test three different methods of incorporating observed nighttime stomatal conductance values to a global land surface model, the Community Land Model (CLM) version 4.5…"*

- Abstract: since this is GMD, it would probably be worth noting in slightly more detail how nighttime conductance was "applied".

Author Response*: We updated the text to be more specific and still brief: "Here, we test three different methods of incorporating observed nighttime stomatal conductance values…" (Abstract, lines 23-4)*

- Abstract/Results: while it is interesting to know that a change in modeled transpiration caused a change in simulated transpiration, and things linked to transpiration, it would be even more interesting to know how these modeled changes compare to the aforementioned empirical observations.

Author Response*: We agree that it is important to evaluate model simulations with empirical observations. We compared our simulations with transpiration estimated from sap flux data in May, June, and July at a point in Australia in Fig. 5. There are numerous caveats associated with these types of comparisons however. First, comparison of sap flow data (even that which is scaled to the canopy level) against the CLM output is problematic because of the absence of a true hydrodynamic model in the CLM4.5 (this will likely be rectified for CLM5, and thus we will be able to make these comparisons). Subsequent to this, canopy level stomatal conductance at night is hard to measure both in-situ and from towers (as you likely know). Third, comparisons of the global model parameterization, generated from average PFT parameters and* *using gridded reanalysis meteorology is problematic (we did not have access to the meteorological data for the semi-arid sap flow sites that observed nighttime transpiration). One goal of this paper to encourage more measurements that will be useful in improving Ball-Berry parameterizations so that we can better constrain and evaluate models in the future. Our primary aim is thus to highlight the high sensitivity of the hydrological and carbon cycles to these typically poorly considered parameters. We highlight the global-scale ecosystem feedbacks to emphasize that nighttime conductance is an important process to constrain.*

- There is some argument that says that nighttime transpiration could actually increase/improve carbon gain because of xylem refilling, i.e., there is water already ready to go once the first daylight hits. I would like to see this analysis in this paper.

Author Response*: We now include additional text in the introduction (Section 1, lines 65-6) and the results and discussion (Section 3.1, lines 256-7) to highlight that xylem refilling might improve carbon gain. However, we cannot decisively state what this relationship might be as there are few, if any, studies that quantify how refilling and nighttime water loss are correlated. Further, it is difficult to make conclusions on the role of refilling in the absence of a hydrodynamic model, since to do so would require a consideration of the costs and benefits of alternate plant hydraulic strategies via their impacts on e.g. leaf water potential and xylem embolism levels, neither of which are represented in the CLM.*

- P10341L2: can you list which of the "many" models use only two g0 values?

Author Response*: The stomatal conductance algorithm in the CLM is based on the implementation in SiB2 (Sellers et al. 1996) and SiB2-based models, and many other land-surface models have similar algorithms. The ORCHIDEE model (used in IPSL-ESM; by Anav et al. 2012) and the CABLE (CSIRO Atmosphere Biosphere Land Exchange)* model *(Kowalczyk et al. 2006) both use the same BWB formulation as the CLM but adjust* g_1 *rather than* g_o *in response to soil moisture deficit. The JULES model (Cox et al. 1998, Best et al. 2011) uses a simplification of the Leuning stomatal conductance algorithm within which it is assumed that* g_o *is zero. The JS-BACH model used in the Max Planck Institute ESM (Raddatz et al. 2007, Brovkin et al. 2009), is based on the BETHY canopy model (Knorr 2000), which uses an alternative stomatal configuration decoupled from assimilation rates. We have not done a comprehensive survey of all land surface models, however, so including a list would not be appropriate. Instead, we now clarify the text to be more specific to the representation of stomatal conductance in CLM. The text is updated to (Section 1, lines 73-4): "The Community Land Model (CLM), however, uses only two* g_o *values…"*

- Methods: what does the "SP" in CLM4.5SP stand for? Satellite phenology? (I had to Google that).

Author Response*: The "SP" signifies satellite phenology, which means that the leaf area index is prescribed from a file. Since most readers would not understand the phrase "satellite phenology", we previously simplified by stating "… with prescribed leaf area indices…". We now explicitly state, "…forced with a data atmosphere and driven with observed ('satellite phenology') leaf area indices (CLM4.5SP)…" (Section 1, lines XX).*

- Methods: more description should be given to how the empirical values were collated for representativeness to PFTs, and the statistical implications and/or error propagation.

Author Response*: We describe the data collation in Section 2.2, provide raw data in SI Table 1, and the data used within the CLM4.5 in Table 1. In SI Table 1, we include the species and the study, as well as the PFT bin that we used for collating the data for the parameterization. In Table 2, we present the mean, median, and standard deviation values, as well as the number of data points per PFT bin. We also present figures from simulations run with the median values (SI Figs 2 and 3), and show the range of error (SI Fig. 1). We now include this information in Section 2.2, lines 141-146. In Section 3.2, we discuss the difference between using mean and median values (lines 294-5), and in Section 3.1 (lines 187-9) we discuss the impact of accounting for variability in the dataset.*

- Results: it is really hard to see the difference between the blue and green lines (the red line isn't great either) in Fig. 1. A re-draw of Fig.1 is in order.

Author Response*: We modified Fig. 1 to make the lines thicker and more easily distinguishable.*

- Results: "...(Fig. 5) illustrates that a minimum gs threshold improves transpiration estimates during the early part of the night..." This is really not illustrated. The color lines at night are barely distinguishable from one another, except maybe in July, but then the difference between simulated and observed is so different that it's hard to see the improvement. Fig. 5 does illustrate, however, that the model updates really actually didn't do much for total nighttime transpiration. This is both interesting and odd, given that I would expect some nighttime transpiration! Looking forward to a revised paper (or a convincing rebuttal to my critiques, which were harsh, I know, sorry). Best wishes, Josh Fisher

Author Response*: We have updated this to say "…(Fig 5) illustrates that a minimum g_s threshold changes transpiration estimates…". We agree that it is not accurate to state that this is an improvement when the changes are very similar among the different methodologies used. This is in part due to the low soil water availability at this site, which down-regulates the nighttime thresholds. The VPD also likely plays a role, as it directly controls transpiration rates. In the text, we do acknowledge that*

"…simulated nighttime rates are still low compared to observations, but fall within the range of observed variability."

Citations used in Author Responses*:*

Ogle K, Lucas RW, Bentley LP *et al.* (2012) Differential daytime and nighttime stomatal behavior in plants from North American deserts. *New Phytologist,* **194**, 464-476.

Cavender-Bares, J., Sack, L. & Savage, J. Atmospheric and soil drought reduce nocturnal conductance in live oaks. *Tree Physiology* **27,** 611–620 (2007).

Anav, A., Menut, L., Khvorostyanov, D. and Viovy, N., 2012. A comparison of two canopy conductance parameterizations to quantify the interactions between surface ozone and vegetation over Europe. *J. Geophys. Res*, *117*, p.G03027.

Cox, P. M., Chris Huntingford, and R. J. Harding. "A canopy conductance and photosynthesis model for use in a GCM land surface scheme." *Journal of Hydrology* 212 (1998): 79-94.

Best, M.J., Pryor, M., Clark, D.B., Rooney, G.G., Essery, R., Ménard, C.B., Edwards, J.M., Hendry, M.A., Porson, A., Gedney, N. and Mercado, L.M., 2011. The Joint UK Land Environment Simulator (JULES), model description–Part 1: energy and water fluxes. *Geoscientific Model Development*, *4*(3), pp.677-699.

Raddatz, T.J., Reick, C.H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K.G., Wetzel, P. and Jungclaus, J., 2007. Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century?. *Climate Dynamics*, *29*(6), pp.565-574.

Brovkin, V., Raddatz, T., Reick, C.H., Claussen, M. and Gayler, V., 2009. Global biogeophysical interactions between forest and climate. *Geophysical Research Letters*, *36*(7).

Knorr, W., 2000. Annual and interannual CO2 exchanges of the terrestrial biosphere: Process-based simulations and uncertainties. *Global Ecology and Biogeography*, *9*(3), pp.225-252.

Comments from Anonymous Reviewer #2

This is a well written manuscript that makes a valuable scientific contribution highlighting the sensitivity of terrestrial ecosystem simulations to the parameterization of stomatal conductance. The authors use a novel dataset of nighttime stomatal conductance to inform simulations in a global land surface model showing that in some simulations global evapotranspiration is increased and runoff reduced. My main criticism is that the attribution of the effects in the simulations to nighttime conductance and transpiration is not entirely accurate. Figures 4 & 5 show that the modified model structures make by far the largest impact on daytime transpiration and not nighttime. And that the g0 and gmin simulations tend to over-predict daytime transpiration in July, the time when these simulations diverge the most from the control and the gnight simulations. This should be discussed in depth. Figure 5 also shows that the modified model structures only very slightly improve simulations of nighttime transpiration. In these simulations of modified stomatal conductance, the main effects result from changes in daytime stomatal conductance, not nighttime stomatal conductance. Though this result is touched on in the manuscript it is not well emphasised. The effects on daytime stomatal conductance and fluxes should be more prominently discussed as it is the major finding from this work and it implies that future efforts should focus on better characterising minimum stomatal conductance during the day. Given this, the title is somewhat misleading as it implies that realistic nighttime conductance leads to changed nighttime transpiration which affects global fluxes, the title should reflect the fact that it is really the change to minimum conductance that is affecting the global fluxes.

Author Response*: We agree that one main effect – the difference between the Δg_{min} and Δg_{night} simulations – results from changes in daytime stomatal conductance, and we did not emphasize this enough in the original manuscript. We now include additional text throughout Sections 3 and 4 to better emphasize this result and highlight the need for additional empirical data. In Section 3.1, we discuss the possible different functionality of minimum and nighttime conductance, including potential physiological reasons, and stress the need for additional observations to discern between these possible parameterizations (see text in Section 3.1, lines 237 to 269). Additionally, we add text in Section 3.2 (lines 307-308) to emphasize that the differences between the two simulations is largely due to changes in daytime minimum conductance, both in hydrologic changes (discussion related to Fig. 2) and terrestrial coupling changes (discussion related to Fig. 4). We also included text in the conclusion (Section 4) to more clearly emphasize the key uncertainty of minimum daytime conductance to differentiate between using the Δg_{min} or the Δg_{night} parameterization.*

We also add text to Section 3.3 to clarify the interpretation of Fig. 5 (see lines 357-366). The data from Fig. 5 are from model simulations that do not use the meteorological data from the Castlereagh site because the required data inputs for CLM were not available from the site. Therefore, the various parameterizations were affected more by the difference in important key parameters like VPD and soil water availability than they were by the difference in parameterization, noted by the fact that different parameterizations were typically more similar to each other than to the observed sap flux data. This is also likely why the nighttime transpiration rates are still too low compared to observations. On a similar note, because the minimum conductance parameterizations only slightly improve nighttime transpiration simulations, as noted by the reviewer, we update the text to note that the parameterizations change (rather than "improve") transpiration in the early parts of the night.

The global fluxes are changed by both nighttime and minimum conductance, though the changes are larger when adjusting minimum conductance. Since our analysis focuses primarily on testing the different methods of modeling conductance and determining the impact of each method on global hydrology and carbon budgets, we feel that the title should not solely focus on minimum conductance. Additionally, it is still unclear whether measured nighttime conductance is truly equivalent to minimum conductance, and we emphasize this point in the paper. Thus, in trying to accurately represent our study objectives and findings, while not specifically focusing on minimum conductance, we update our title to: "Incorporating observed nighttime conductance alters global hydrology and carbon budgets in CLM4.5".

Minor comments: p8 ln16 – I think you mean lower daytime gs than night-time. p9 ln25 – this should also be described in the methods.

Author Response*: Yes, thank you for catching the typo on page 8. We do include the soil water scalar adjustment in the methods (as in page 9), but did not previously include the variable name. We have updated Section 2.1 to include the* β_{soil} *variable name so that the methods and the text in Section 3 are more explicitly linked.*

P10 ln2-4 – this statement is not true. Water loss is not just a function of stomatal conductance. In the Penmen-Monteith formulation of evapotranspiration insolation, vpd, and wind speed are the drivers of water loss. Insolation is zero at night and vpd and wind speeds are generally lower so it is unlikely that higher nighttime gs leads to higher water loss during the night compared with the day.

Author Response*: In making this statement, we assumed this was true when other variables were held constant. To minimize confusion, we remove this statement from the discussion.*

Figure 5 – why isn't the whole 24 hr period shown for May?

Author Response*: The model calculates fluxes in GMT, so we had to adjust the time in the CLM so that the simulated fluxes matched the fluxes at the same time recorded for the observations and in the model simulation. Due to this time adjustment, the data for the month of May start at 11:00 local time.*

Comments from Executive Editor Astrid Kerkweg

In my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1:

http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html

This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section:

http://www.geoscientific-model-development.net/submission/manuscript_types.html In particular, please note that for your paper, the following requirements have not been met in the Discussions paper:

Author Response*: Thank you for bringing to our attention the GMD publishing requirements.*

- "The main paper must give the model name and version number (or other unique identifier) in the title."

Author Response*: We now include the model name and version number (CLM4.5) in the title.*

- "If the model development relates to a single model then the model name and the version number must be included in the title of the paper. If the main intention of an article is to make a general (i.e. model independent) statement about the usefulness of a new development, but the usefulness is shown with the help of one specific model, the model name and version number must be stated in the title. The title could have a form such as, "Title outlining amazing generic advance: a case study with Model XXX (version Y)"."

Author Response*: We now include the model name and version number (CLM4.5) in the title.*

- "All papers must include a section, at the end of the paper, entitled 'Code availability'. Here, either instructions for obtaining the code, or the reasons why the code is not available should be clearly stated. It is preferred for the code to be uploaded as a supplement or to be made available at a data repository with an associated DOI (digital object identifier) for the exact model version described in the paper. Alternatively, for established models, there may be an existing means of accessing the code through a particular system. In this case, there must exist a means of permanently accessing the precise model version described in the paper. In some cases, authors may prefer to put models on their own website, or to act as a point of contact for obtaining the code. Given the impermanence of websites and email addresses, this is not encouraged, and authors should con- sider improving the availability with a more permanent arrangement. After the paper is accepted the model archive should be updated to include a link to the GMD paper."

Author Response*: The CLM4.5 is publically available through Subversion code repository. We now include a link to the code, as well as the registration to get the required user name and password, and links to the Technical Description and User's Guide.*

- Inclusion of Code and/or data availability sections is mandatory for all papers and should be located at the end of the article, after the conclusions, and before any appendices or acknowledgments. For more details refer to the code and data policy.

Author Response*: We now include a "Code and Data Availability" section at the end of the paper. This section describes how to obtain the model code, and also points readers to the supplemental table where all the data we used to develop the new minimum conductance parameters are collated.*

Incorporating observed nighttime conductance alters global hydrology and carbon budgets in CLM4.5.

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Abstract

The terrestrial biosphere regulates climate through carbon, water, and energy exchanges with the atmosphere. Land surface models estimate plant transpiration, which is actively regulated by stomatal pores, and provide projections essential for understanding Earth's carbon and water resources. Empirical evidence from 204 species suggests that significant amounts of water are lost through leaves at night, though land surface models typically reduce stomatal conductance to nearly zero at night. Here, we test three different methods of incorporating observed nighttime stomatal conductance values to a global land surface model, the Community Land Model (CLM) version 4.5, to better constrain carbon and water budgets. We find that our modifications increase transpiration up to 5% globally, reduce modeled available soil moisture by up to 50% in semi-arid regions, and increase the importance of the land surface in modulating energy fluxes. Carbon gain declines up to ~4% globally and >25% in semi-arid regions. We advocate for realistic constraints of minimum stomatal conductance in future climate simulations, and widespread field observations to improve parameterizations.

1. Introduction

Terrestrial plants must balance their need to obtain CO_2 with the risk of desiccation if transpiration continues unchecked. Higher plants evolved stomatal pores to control the exchange of water and carbon between the leaf interior and the atmosphere (Hetherington and Woodward, 2003). Stomatal function, thus, is the dominant control over terrestrial fluxes of water and carbon. Most large-scale land-surface models use an empirical representation of stomatal conductance (g_s), similar to the Ball-Woodrow-Berry (BWB) model (Ball, 1988; Ball et al., 1987; Collatz et al., 1991; Leuning, 1995; Medlyn et al., 2011; Sellers et al., 1996), to calculate plant gas exchange. The BWB model is linear, with two constants, the intercept (g_o) and slope (g_1), and estimates g_s from the rate of CO_2 assimilation (A), atmospheric humidity (h_r), and internal leaf CO_2 concentration. The original BWB model parameters were fitted to observations of leaf gas exchange for ten plant species, with different g_o values for each species, ranging from -310 to 130 mmol m^{-2} s^{-1} (Ball, 1988). The Community Land Model (CLM), however, uses only two g_o values, (10 and 40 mmol m^{-2} s^{-1} for C_3 plants and C_4 plants, respectively; Collatz et al., 1991; Oleson et al., 2013; Sellers et al., 1996). Conductance during the night (and at other times when A is 0) is thus represented using g_o. Recent advances in our ability to observe nighttime stomatal conductance (Caird et al., 2007; Phillips et al., 2010), $g_{s,n}$, illustrate that values are often larger in the field than the BWB parameters used in the CLM.

A comprehensive database (see Table S1) of 204 observed $g_{s,n}$ values illustrates that the minimum BWB g_s values (equivalent to g_o) used in the CLM starkly differ with observed mean and median $g_{s,n}$ values. The available data for $g_{s,n}$ range from 0-450 mmol m^{-2} s^{-1} with an overall mean of 78 mmol m^{-2} s^{-1} (excluding hemi-parasites and CAM plants, which were omitted from model testing). Observations of $g_{s,n}$ are, on average, ten times higher in broadleaf tropical deciduous species (Table 1; 129 mmol m^{-2} s^{-1}) and seven times higher in temperate broadleaf deciduous trees (73 mmol m^{-2} s^{-1}) compared to the 10 mmol m^{-2} s^{-1} used for C_3 plants. Potential benefits of a high $g_{s,n}$ might include the transport of nutrients (Dios et al., 2013; Scholz et al., 2007; Zeppel et al., 2014) or processes related to embolism repair, phloem transport, or xylem refilling that might improve carbon gain, but these ideas remain untested. Nonetheless, the discrepancy between parameterized g_o and observed $g_{s,n}$ serves as motivation to investigate the sensitivity of simulated land surface processes to more realistic minimum g_s values. Such field measurements of $g_{s,n}$ have not previously been incorporated into a global land surface model, despite the possible impacts on surface hydrology, ecosystem carbon gain, and land-atmosphere feedbacks.

We use a global land-surface model, the Community Land Model (CLM) version 4.5, forced with a data atmosphere and driven with observed ('satellite phenology') leaf area indices (CLM4.5SP), to test the sensitivity of the land surface to using realistic minimum g_s from observed $g_{s,n}$, averaged by plant functional type (PFT; Table 1). Since the BWB approach is primarily intended to predict daytime stomatal behavior, the appropriate method for application of observed $g_{s,n}$ within the context of the BWB model is unclear. We therefore test three methodologies for implementing observed $g_{s,n}$: 1) modifying the BWB intercept (g_o); 2) setting a nighttime threshold value; and 3) setting a minimum threshold value. We anticipate that implementing observed $g_{s,n}$ values will increase plant transpiration, altering carbon and water budgets on regional and global scales.

2. Methods

2.1 Modeling

The CLM4.5SP model used here is an updated version of CLM4.0, originally described by Lawrence et al., (2011), with updated technical details for v4.5 described by Oleson et al., (2013). The CLM4.5SP simulations were run with

CRU-NCEP climate forcing data (combines Climate Research Unit (CRU) TS 3.2 monthly climatology with National Oceanic and Atmospheric Administration National Center for Environmental Prediction (NCEP) and NCAR 2.5° x 2.5° 6-hourly reanalysis; (downloaded at: http://dods.ipsl.jussieu.fr/igcmg/IGCM/BC/OOL/OL/CRU-NCEP/), a historical atmospheric dataset that includes observed precipitation, temperature, downward solar radiation, surface wind speed, specific humidity, and air pressure from 1901 through 2010, and did not include the influences of nitrogen deposition, land use change, or changing CO_2 concentrations.

The CLM4.5SP uses the coupled Farquhar photosynthesis and BWB g_s models to simulate plant physiology (Bonan et al., 2011; Oleson et al., 2013). The BWB g_s is calculated based on the equation:

$$g_s = g_0 + g_1(Ah_r/C_a) \quad \text{(Eq. 1)}$$

where g_0 and g_1 are empirical fitting parameters of the minimum g_s and the slope of the conductance-photosynthesis relationship, respectively; A is net carbon assimilation rate (μmol C m^{-2} s^{-1}); h_r is the fractional humidity at the leaf surface (dimensionless), and C_a is the CO_2 concentration at the leaf surface (μmol mol^{-1}). When implemented in the unmodified CLM4.5SP, g_0 is 10 mmol m^{-2} s^{-1} for all C_3 plants and 40 mmol m^{-2} s^{-1} for all C_4 plants, and is adjusted by a soil wetness factor (varying from 0-1) every time-step.

Values of $g_{s,n}$ based on literature data (Table S1) are typically larger than the g_0 values used in current implementations of the BWB model. The $g_{s,n}$ data, grouped and then averaged by PFT (Table 1), were used to modify simulated minimum g_s using three methodologies. First, the 'Δg_0' method replaced the BWB minimum conductance, g_0, value for each simulated PFT with the observed $g_{s,n}$

(Table 1), resulting in a uniform increase to g_s during both day and night (referred to as the Δg_o simulation; tested previously by Barnard and Bauerle, 2013). Second, the Δg_{night} method implemented the BWB model in its standard form (Eq. 1; the g_o and g_1 values are the same as the control), but included a minimum threshold that was applied only at night, based on observed $g_{s,n}$ for each PFT, below which g_s could not fall. In the Δg_{night} simulation, daytime Δg_s occasionally fell below the observed nighttime threshold on account of high vapor pressure deficit (VPD) or low assimilation rates. To avoid this potentially unrealistic behavior, we use a third method, 'Δg_{min}', which extended the observation-based threshold used in the Δg_{night} simulation to all times during the day or night, so that g_s never fell below the minimum threshold value found in Table 1. These three modified simulations were compared to a control simulation using the unmodified BWB formulation. Similar to the unmodified simulation that adjusts the g_o parameter based on a soil wetness scalar (β_{soil}), the Δg_{night} and Δg_{min} modifications also adjusted the minimum g_s threshold by a soil wetness scalar, β_{soil}, that ranges from zero to one, at every time-step. Each simulation was run for 25 years with monthly output to determine the long-term impact of changing minimum conductance, and for one year with half-hourly output to determine the changes in diel patterns.

2.2 Data Collection

Values of $g_{s,n}$ were obtained from field and glasshouse studies, using Scopus (www.scopus.com), with data for 204 records across 150 species and cultivars (Table S1). Records available were predominately for temperate plants (93 records) and crops (34), with more data available for broad-leaf plant types

(89) than needle-leaf plants (16; Zeppel et al., 2014). The data were collated by plant functional type (PFT), with means, medians, and standard deviations for each PFT presented in Table 1. Simulations presented here were run with mean values for each PFT, though median values were also tested and are presented in SI Figure 3 and SI Figure 4. Since there is large variability in the PFT responses, we present the range of variability in SI Figure 2.

The measurements of each $g_{s,n}$ value are generally obtained from steady state porometers, diffusion porometers, Licor 1600 and Licor 6400 gas exchange systems (Caird et al., 2007; Phillips et al., 2010), with a small number converted from sap flux (Benyon 1999) using an inverted Penman-Monteith equation. Different sampling methods may lead to different estimates of $g_{s,n}$, and measureable $g_{s,n}$ typically only occurs where VPD is above zero. For example, using a cuvette clamped over the leaf, which changes the leaf boundary layers, will be different compared to measurements from sap flow with an unaltered boundary layer. Data for $g_{s,n}$ were typically reported during well-watered conditions, which is ideal because the CLM4.5 calculates stomatal g_s without water stress and then adjusts g_o values (and modifications additionally adjust g_{night} and g_{min} thresholds) using a soil wetness scalar.

2.3 Terrestrial Coupling Index

To investigate the impact of stomatal conductance changes on the degree to which land processes exert influence over the atmosphere, a terrestrial coupling index was calculated, allowing examination of the influence of a minimum g_s threshold on land-atmosphere coupling. Following Dirmeyer (2011), the terrestrial segment of land-atmosphere coupling is defined as:

$$\text{Terrestrial Coupling Index (TCI)} = \sigma_w * \beta_{w,ET} \qquad \textit{(Eq. 2)}$$

where σ_w is the standard deviation of root-zone soil moisture relevant for transpiration across a given season (e.g., 25 years times 3 summer months), and $\beta_{w,ET}$ is the linear slope of monthly mean evapotranspiration and root-zone soil moisture. The TCI captures the variability (σ_w) and sensitivity of evapotranspiration to changes in soil moisture and returns units equivalent to those of evapotranspiration. Therefore, for a region to have high TCI, soil moisture must have high variability thus enabling any evapotranspiration-soil moisture sensitivity to manifest in the climate system. While this is strictly a metric for defining the terrestrial component of coupling, the terrestrial component has been used as a surrogate for the total soil moisture-precipitation coupling pattern because of the strong spatial pattern correlation (Wei and Dirmeyer, 2012).

3. Results and Discussion

3.1 Implementation of $g_{s,n}$

Incorporating observed minimum constraints on g_s in all modified simulations increased g_s and transpiration compared to the control simulation, illustrated in Fig. 1 for a highly impacted semi-arid location in Ethiopia (see Fig. S1 for other regions). The large variability in the observational dataset causes substantial uncertainty in the simulations, masking the differences among parameterizations and highlighting the impact of $g_{s,n}$ on transpiration (Fig. S2). The sensitivity of g_s and transpiration to the altered g_o parameter in the Δg_o

simulation is large (Barnard and Bauerle, 2013; Bowden and Bauerle, 2008). Since the higher g_o is added to g_s in the BWB calculation at every model time step (see Eq. 1), altering g_o increases transpiration throughout the entire diel cycle, and produces changes in the daytime evaporative flux that are not supported by observations of $g_{s,n}$. We consider that uniformly adjusting the g_o parameter does not represent the correct implementation of observed $g_{s,n}$ values.

If g_o cannot be equated to plant minimum g_s in the BWB paradigm, this raises the possibility of whether g_o has a theoretical interpretation beyond an empirical fitting parameter. It is possible that g_o is equivalent to cuticular conductance (g_{cut}), or conductance that is not regulated by the stomatal guard cells (Caird et al., 2007), occurring during the day and night. Niyogi and Raman (1997) describe g_o as cuticular conductance, though there is no record of g_o being tested or described as g_{cut} previously. Studies that have quantified g_{cut} found that g_{cut} was a low proportion, < 10%, of total g_s and less than measured $g_{s,n}$ (Caird et al., 2007; Zeppel et al., 2014). The values of g_o used in current implementations of the Ball-Berry model for C_3 plants (10 mmol m^{-2} s^{-1}) fall within the range of measured g_{cut} values (4 to 20 mmol m^{-2} s^{-1}; Caird et al., 2007). Assuming g_o does have a theoretical function of representing g_{cut}, rather than $g_{s,n}$, incorporating an observed threshold of minimum g_s is necessary. Whether g_o functions theoretically as g_{cut} in the BWB model needs further evaluation, as adjusting simulated g_o has large impacts on canopy conductance and transpiration (Fig 1; Barnard and Bauerle, 2013). Regardless, observed $g_{s,n}$ is larger than modeled g_o and functions differently, and therefore should be considered independently in model parameterizations.

The Δg_{min} and Δg_{night} simulations represent the intended change in minimum g_s with greater fidelity, by limiting the minimum value without increasing g_s at every model time step. Interestingly, in restricting only nighttime conductance, the Δg_{night} simulation allows daytime g_s to decrease below the nighttime threshold during the dry season in semi-arid ecosystems (Fig. 1a). This occurs when A_n nears zero in shade or low humidity, causing g_s to fall to the default (lower) g_o. In contrast, the Δg_{min} simulation restricts minimum g_s at all times, and therefore daytime values are never less than the water-adjusted $g_{s,n}$. This increases canopy-averaged daytime g_s, and hence transpiration, compared to the unmodified simulation whenever daytime g_s values fall below the minimum threshold (Fig. 1a, c).

The data in Table S1 is a compilation of all available published $g_{s,n}$ data to date, and reports $g_{s,n}$ values for 204 distinct plants. Of these, only four plants exhibit higher $g_{s,n}$ than daytime g_s, and two of those are Crassulacean acid metabolism (CAM) plants, which by definition open their stomata at night to gain carbon dioxide and close their stomata during the day, and were not used in our parameterization. These data suggest that, as expected, $g_{s,n}$ is typically less than daytime g_s. Most data presented in Table S1 are average values under non-drought stressed conditions, and are likely only reported for leaves in sunlit canopy layers. Thus, these data do not elucidate whether, at any given time, daytime values might drop below the nighttime threshold, but only suggest that, on average, they do not.

In the context of the model simulations, low daytime g_s occurs any time that Ah_r/C is low. These are conditions which are poorly illuminated (in shade or at dawn/dusk and night), or when humidity is low. The CLM4.5SP contains a representation of the shaded canopy, which has lower g_s and often reaches the minimum daytime threshold (g_o in the unmodified, Δg_o, and Δg_{night} simulations; and $g_{s,n}$ in the Δg_{min} simulation). The central issue in determining whether the Δg_{min} or Δg_{night} simulation is a better representation of minimum g_s is whether, under the same conditions in the real world, daytime g_s might be lower than $g_{s,n}$. For example, if observational data support that daytime g_s is less than $g_{s,n}$ in shaded canopy layers, then the Δg_{night} simulation is a better parameterization. However, if observational data suggest that daytime g_s is consistently higher than $g_{s,n}$, then the Δg_{min} simulation is a better parameterization. While observational data are not available to specifically answer this question, the available data (presented in Table S1) imply that daytime g_s is on average higher than $g_{s,n}$, providing partial support for the Δg_{min} implementation.

The possible existence of a higher $g_{s,n}$ compared to daytime g_s raises an interesting question about the potential selective advantage for leaves with a high $g_{s,n}$. It is hypothesized that high $g_{s,n}$ may provide a beneficial function to the plant, such as embolism repair or phloem transport. Additionally, $g_{s,n}$ may contribute to xylem refilling, potentially improving carbon gain by making water available when light conditions allow for photosynthesis. Critically, it is not clear whether these potential functions are only relevant at night (and daytime g_s can be lower than $g_{s,n}$), or whether high $g_{s,n}$ is representative of a general strategy of higher overall minimum g_s. We are not aware of data that exist to support either possibility, and advocate for observations that will help determine the functional significance of $g_{s,n}$.

From a model or theoretical perspective, it is important to note that the reason that simulated g_s values are reduced to as low as 10 mmol m^{-2} s^{-1} (or lower, if down-regulated for water stress) is a function of the universal parameterization of all C_3 plants with that value of g_o. Given that it is unlikely that this value is universal for all plants, we consider that the large difference between the Δg_{min} or Δg_{night} simulations is an artifact of the poorly constrained parameterization of the daytime BWB model.

It should be noted that all the minimum thresholds implemented in our simulations (Δg_o, Δg_{night}, and Δg_{min}) are adjusted by a soil water scalar (β_{soil}). Therefore, the nighttime (Δg_{night}) and the minimum (Δg_{min}) thresholds are altered according to the degree of soil moisture stress. When the daytime g_s value is lower than the g_{night} threshold in the Δg_{night} simulation (Fig. 1c), the g_{night} threshold is already down-regulated for water stress. In this scenario, the daytime minimum g_s is less than the nighttime g_s when water stress is equivalent.

Responses to dry soil conditions are mediated both through the minimum g_s values, and through the impact of soil moisture on photosynthetic capacity and leaf maintenance respiration, which are also multiplied by $\beta_{soil.}$ Many of the impacts of our simulations result from feedbacks between higher transpiration rates resulting in faster depletion of soil moisture store, and therefore greater constraint on photosynthesis. These results are all emergent features of the model and should not be interpreted as direct results of the altered parameterization.

3.2 Global Water and Carbon

When averaged over 25 years, incorporating observed rates of $g_{s,n}$ in the Δg_{min} simulation increased transpiration losses up to 30% in the Amazon, and >30% in some arid regions, in part due to the small absolute magnitude of available soil water (Fig. 2a-c). Semi-arid regions are primarily broad-leaf shrub and C_3 grass PFTs that have particularly high values (130 and 156 mmol m^{-2} s^{-1} respectively) of observed $g_{s,n}$ (Table 1), and have high nighttime vapor pressure deficits that interact with higher minimum g_s values, causing large nighttime transpiration rates. Using median rather than mean values caused only small (<1.5%) differences in global transpiration (Fig. S3, Fig. S4). Though the magnitude of response is different depending on parameterization used, the increases in transpiration imply that current model estimates of plant water loss are underestimated in many regions.

Simulated higher transpiration resulting from higher minimum g_s also has ecosystem-scale ramifications for hydrology (McLaughlin et al., 2007). For example, the increased transpiration resulted in drier soils compared to the control simulation (Fig. 2g-i), with Δg_{min} causing >40% soil moisture decreases in semi-arid ecosystems like the Southwestern United States and much of Australia (>10% in Δg_{night}). Additionally, the Δg_{min} estimated changes to surface runoff are large in some regions, such as the 10-25% decreases in the tropics (5-10% in Δg_{night}; Fig. 2d-f), suggesting that current runoff estimates may be too large. It should be noted that the difference between the Δg_{min} and Δg_{night} simulations is largely due to changes in minimum g_s that affect daytime g_s (see Section 3.1). Hydrologic changes in soil moisture and runoff in response to increased g_s have previously been documented in catchments in southeastern United States (McLaughlin et al., 2007), and our results suggest that changes to stomatal conductance have similar consequences in CLM4.5SP simulations. Additionally, increasing minimum g_s caused gross primary productivity (GPP) to decrease (Figure 3) by 10 to >25% in many semi-arid regions. These are regions where water availability already restricts GPP, and the decreases in soil moisture caused by higher transpiration likely impart even more drought-induced stomatal closure.

To more directly evaluate the potential influence of minimum g_s on the climate system, we calculate the change in terrestrial coupling to the atmosphere. The terrestrial coupling index (Dirmeyer, 2011) estimates the degree to which changes in soil moisture control surface energy fluxes to the atmosphere. This study uses root-zone soil moisture rather than soil moisture over spatially constant soil depth to highlight the direct impact of vegetation and minimum g_s on surface fluxes. Here we calculate the terrestrial coupling index during boreal summer months when warmer temperatures allow for the highest g_s rates. We find that the terrestrial coupling strength increases when using the Δg_{min} implementation, but is generally unchanged for Δg_{night} (Fig. 4), meaning root-zone soil moisture exerts a greater control on surface flux variability for Δg_{min}, largely due to the impact this simulation has on daytime g_s. This increased terrestrial coupling to the atmosphere largely mirrors the reductions in GPP and soil moisture in semi-arid ecosystems, and may reinforce climate extremes such as droughts or heat waves (Hirschi et al., 2011; Miralles et al., 2014).

3.3 Evaluating $g_{s,n}$

Evaluating the performance of the new $g_{s,n}$ parameterizations is challenging for numerous reasons. First, our model scales from leaf-level g_s and $g_{s,n}$ estimates to canopy transpiration. The best way of evaluating the model is to compare simulated and observed canopy transpiration because the model captures the average of an entire canopy, which is comprised of multiple plant functional types, rather than individual plant functional types. Incorporating realistic minimum g_s increases global evapotranspiration and decreases global runoff compared to globally-scaled observations, while estimates of GPP from all simulations fall within the range of global GPP estimates from observations (Table 2; Bonan et al., 2011, 2012; Li et al., 2011). However, these comparisons should be used with caution, since eddy covariance data used in estimating the GPP and evapotranspiration observations are susceptible to errors at night (Fisher et al., 2007; van Gorsel et al., 2008; Kirschbaum et al., 2007; Medlyn et al., 2005) due to a lack of sufficient canopy turbulence that precludes detection of nighttime transpiration using this measurement methodology, and are not useful for evaluating the changes in water fluxes tested in this study. Other data for evaluating model responses to minimum g_s on large spatial scales are not yet available.

A comparison of simulated canopy transpiration to transpiration calculated from sap-flux data in Australia (Fig. 5) illustrates that a minimum g_s threshold changes transpiration estimates during the early part of the night, though simulated nighttime rates are still low compared to observations. All model parameterizations fall within the observational range of uncertainty, but under-predict nighttime and midday canopy transpiration during May and June, and over-predict midday canopy transpiration in July. The lack of fidelity between the various model parameterizations and the observations is likely affected by the fact that observed meteorological data were unavailable to force the model. Therefore, key parameters driving both daytime and nighttime transpiration fluxes, such as VPD and soil water availability, were likely different in the model simulations compared to the actual meteorological conditions at Castlereagh during data collection. Additionally, because sap flow is measured at the base of the tree, there is typically a lag between when sap flow is measured and when the canopy transpires, and this lag is also notable in comparing observed sap flow with simulated estimates of transpiration. Estimating nighttime transpiration using sap flow methodology is also convoluted with the refilling of aboveground water stores depleted during the day, and thus is not directly comparable to our simulations. It should also be noted that the model does not have a semi-arid plant functional type, so semi-arid plants are typically represented in the model as deciduous plant functional types.

Given that our study focused only on one aspect of the g_s formulation within a land surface model, evaluating daytime g_s and other aspects of the BWB model function (i.e., photosynthetic drivers of daytime g_s, feedbacks to water availability, etc.) are all subject to pre-existing deficiencies in the representation of a host of other model processes. For example, there are only two values of the g_1 (slope) parameter in the BWB model, one for C_3 and one for C_4 plants (Sellers et al., 1996), and this parameter has not been modified or comprehensively evaluated within the context of the CLM4.5SP. Indeed, the use of the BWB model at all is currently the subject of some debate (Bonan et al., 2014; De Kauwe et al., 2015). Further, daytime g_s is also dependent on the photosynthetic capacity, and observations of V_{cmax} and J_{max} (Bonan et al., 2011; Kattge and Knorr, 2007) indicate very wide ranges of plant functional type variation in these properties, also limiting our confidence that the globally averaged parameters used in the default model will lead to accurate g_s and transpiration at most locations. We choose not to focus on these and other parameters that effect daytime g_s, as it does not directly impact the representation of $g_{s,n}$, and is therefore beyond the scope of this paper.

4. Conclusion

The rate of minimum g_s estimated from the BWB model used in many global land surface models is typically smaller than observed $g_{s,n}$ (Barnard and Bauerle, 2013), as demonstrated in a review of 204 species (Zeppel et al., 2014). Including a nighttime or minimum g_s threshold based on observations results in simulated hydrologic changes, such as decreased soil moisture and runoff (Fig. 2), particularly in semi-arid regions where water availability already restricts growth. In addition to potentially increasing drought stress in sensitive regions, this has the impact of reducing plant growth (Fig. 3) and changing the modeled terrestrial coupling to the atmosphere (Fig. 4). The difference between the Δg_{min} and Δg_{night} simulations highlights one outstanding uncertainty: Does minimum daytime g_s decrease below nighttime g_s? While the balance of our arguments favors the Δg_{min} implementation of $g_{s,n}$, this study primarily illustrates the potential sensitivity of global simulations to minimum g_s considerations, and serves as motivation for additional field experiments, particularly in semi-arid areas, to discern better representations of low g_s conditions during daytime and nighttime. To better understand the future of these sensitive ecosystems, widespread field observations, quantification of minimum daytime g_s, and a better understanding of the physiological causes and consequences of nighttime transpiration are necessary so that land surface models can robustly incorporate observations and theory.

5. Code and Data Availability

The code for CLM4.5 is publically available through Subversion code repository: https://svn-ccsm-models.cgd.ucar.edu/cesm1/release_tags/cesm1_2_2. To access the code, fill out a short, required registration to get a user name and password, necessary to gain access to the repository. http://www.cesm.ucar.edu/models/register/register_cesm.cgihttp://www.cesm.ucar.edu/models/cesm1.2/clm/CLM45_Tech_Note.pdf. The CLM4.5 User's Guide can be found at: http://www.cesm.ucar.edu/models/cesm1.2/clm/models/lnd/clm/doc/UsersGuide/book1.html. All stomatal conductance data used in developing the implementations can be found in Table S1.

Author Contributions

DL, MZ, and RF conceived the project. MZ assembled the $g_{s,n}$ datasets; DL ran model simulations; and DL and AT analyzed model simulations, with guidance from RF. All authors contributed to writing the paper.

Acknowledgements

We thank Gordon Bonan for useful discussion on the manuscript, and the reviewers for the constructive comments that have improved the final version of this paper. DL was supported through the DEB-Ecosystem Science cluster and National Science Foundations grant EF-1048481. MZ was supported by ARC DECRA DE120100518. RF was supported by the National Science Foundation and the National Center for Atmospheric Research, and AT was supported by the National Science Foundation grant 0947837 for Earth System Modeling postdoctoral fellows. The National Center for Atmospheric Research is funded by the National Science Foundation.

Tables

Table 1. Old and new minimum stomatal conductance values used in CLM4.5SP. Units are mmol m^{-2} s^{-1}

Plant Functional Type	Old Value	Mean New Value	Median New Value	Standard Deviation	n
temperate needle-leaf evergreen tree	10	16.896	10	20.80332642	12
boreal needle-leaf evergreen tree	10	8	8	NA	1
needle-leaf deciduous tree	10	35.367	35	6.457811807	3
tropical broadleaf evergreen tree	10	90.488	75.5	67.85015923	8
temperate broadleaf evergreen tree	10	34.017	27	28.2627804	25
tropical broadleaf deciduous tree	10	129	129	41.01219331	2
temperate broadleaf deciduous tree	10	72.637	41.66	83.52495039	22
boreal broadleaf deciduous tree	10	50	50	NA	1
broadleaf evergreen shrub	10	65.353	29	116.0616668	16
broadleaf deciduous shrub	10	129.644	60	145.5387501	9
c3 grass	10	157.988	161	67.31744598	24
C4 grass	40	93.933	48.5	125.5325881	6
crop	10	60.629	36.7	60.74543722	21
					150

*New Value, Standard Deviation and n are based on data pooled from the literature.

Table 2. Global values from CLM simulations and observations[a]

Simulation	**$g_{s,n}$ data used**	**GPP (Pg C yr^{-1})**	**ET (10^3 km^3 yr^{-1})**	**Runoff (10^3 km^3 yr^{-1})**
Control	N/A	157.83	65.6148	30.462
g_o	Mean	152.56	72.6555	24.2141
g_{night}	Mean	156.068	66.0926	30.0724
g_{min}	Mean	151.252	68.6843	27.8161
g_o	Median	153.641	71.5441	25.1739
g_{night}	Median	156.346	66.031	30.119
g_{min}	Median	152.385	67.8881	28.51
Observation		119-175	65.13	37.7521

[a]Global gross primary productivity (GPP), evapotranspiration (ET) and runoff values. Observed values presented in Bonan et al. (2011), Welp et al. (2011), and Lawrence et al. (2011)

Figure Captions

Figure 1. Diurnal time-series of canopy conductance (a,c) and transpiration (b,d) for Ethiopia over five days in mid-January (a-b) and mid-July (c-d). The control simulation (solid black line) had lower conductance and transpiration than the Δg_o simulation (dotted red line) and the Δg_{min} simulation (dashed blue line). The Δg_{night} simulation (dot-dashed teal line) had higher nighttime conductance and transpiration than the control simulation, but similar daytime conductance and transpiration, allowing for daytime conductance to fall below the nighttime threshold. The Δg_o simulation added the observed $g_{s,n}$ values to the conductance calculation at every time, day or night, which is not theoretically aligned with the function of including observed $g_{s,n}$. As a result, the Δg_o simulation was eliminated from further analyses. Note that all minimum thresholds (g_o, g_{night}, and g_{min}) were adjusted using a soil moisture scalar.

Figure 2. Simulated average transpiration (a), runoff (d), and soil moisture (g) for a control simulation; and percent change from control in transpiration (b-c), runoff (e-f), and soil moisture (h-i) after including a nighttime threshold (Δg_{night}; b,e,h) or a minimum g_s threshold (Δg_{min}; c,f,i) based on observational data. Note that both nighttime and minimum thresholds were adjusted based on a soil moisture scalar.

Figure 3. Average gross primary productivity (GPP) for a control simulation (a), and percent change from control (b-c) after including a nighttime threshold (Δg_{night}; b) or a minimum g_s threshold (Δg_{min}; c) based on observational data.

Note that both nighttime and minimum thresholds were adjusted based on a soil moisture scalar.

Figure 4. Terrestrial coupling for June-July-August for a control simulation (a), and the difference from control (b-c) after including a nighttime threshold (Δg_{night}; b) or a minimum g_s threshold value (Δg_{min}; c) based on observational data. Note that both nighttime and minimum thresholds were adjusted based on a soil moisture scalar.

Figure 5. Average diel canopy transpiration for the months of May, June, and July in Castlereagh, Australia (observation, dotted black line), estimated from sap flux measurements of Red Gum and Iron Bark, the dominant tree species in the canopy. Average simulated canopy transpiration for the grid cell corresponding to Castlereagh, Australia for the control (unmodified; solid black line), Δg_o (Ball-Berry g_o parameter adjusted; red line), Δg_{night} (minimum nighttime threshold added; teal line), and Δg_{min} (minimum conductance threshold added; blue line) simulations. Error bars corresponding to the observations (dashed) and each simulation (solid) are colored accordingly, and are calculated as +/- one standard deviation from the mean. Note that the simulations use meteorological forcings from an atmospheric dataset (see Methods), not the local meteorology from when the measurements were collected (some meteorological data was collected at the site, but not all variables required by the model). The simulated grid cell covers a much larger area than the observational data collection site.

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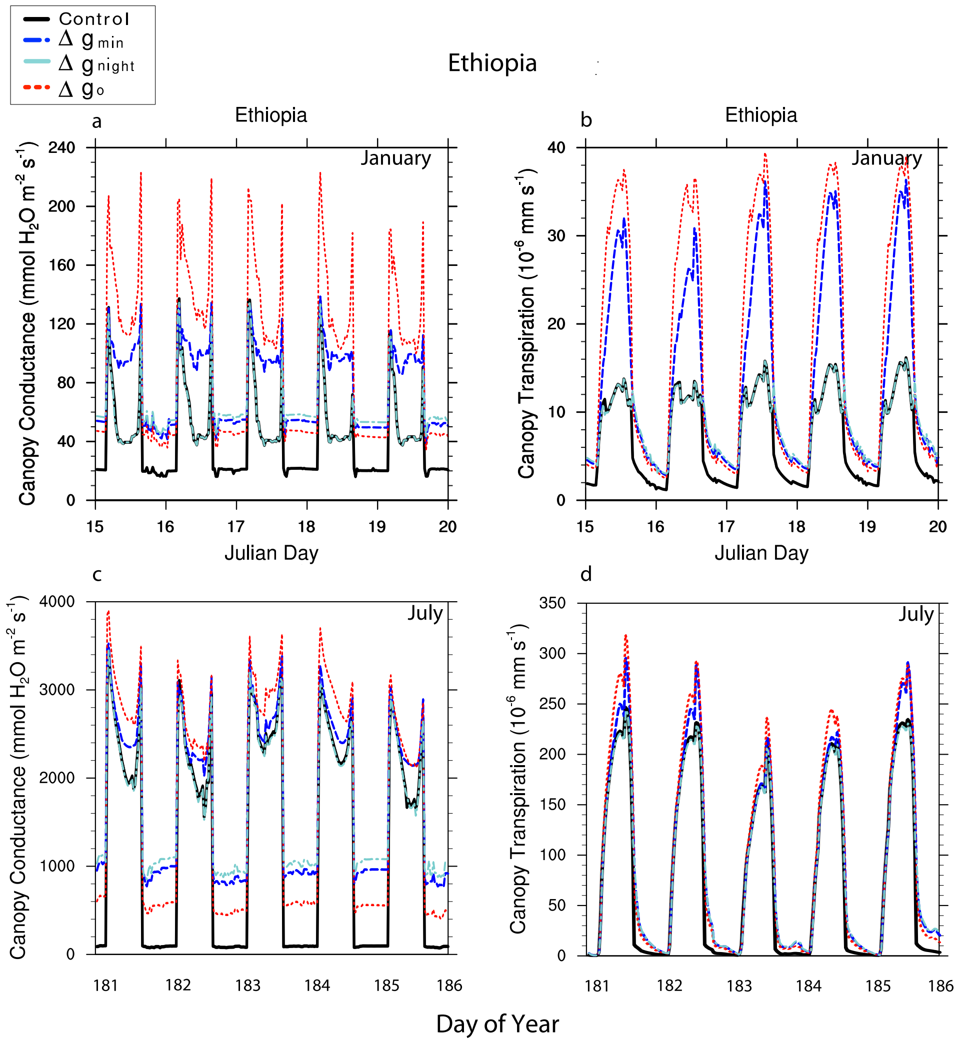
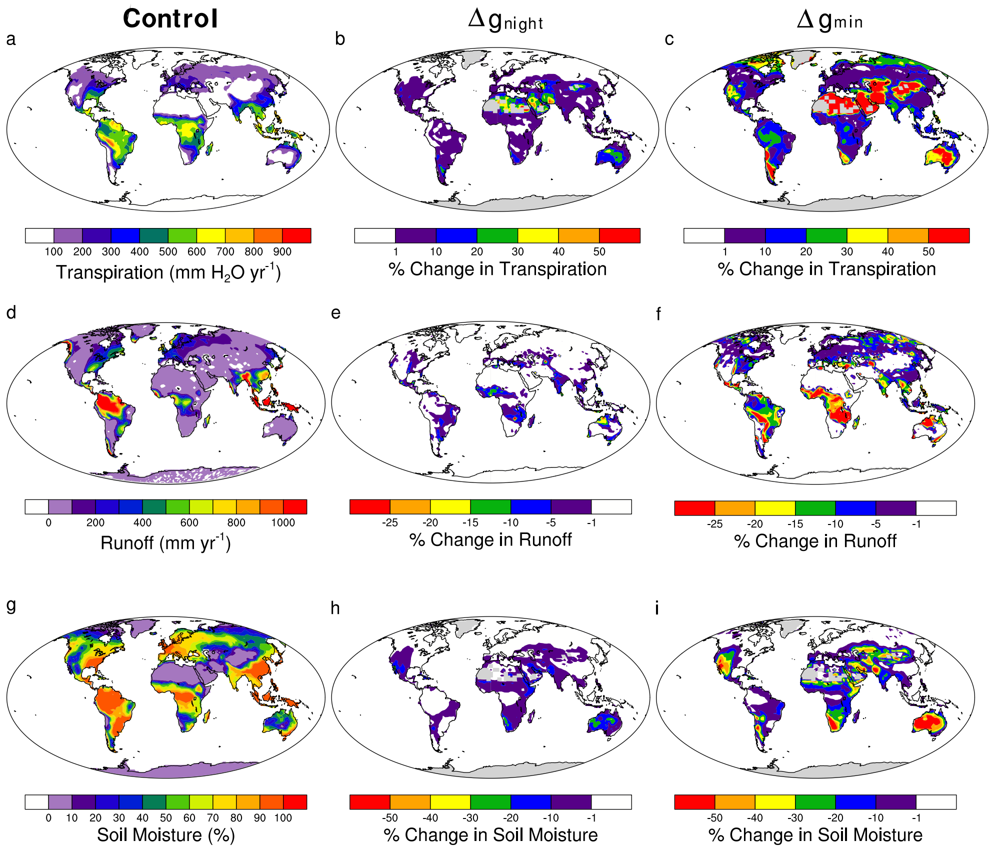
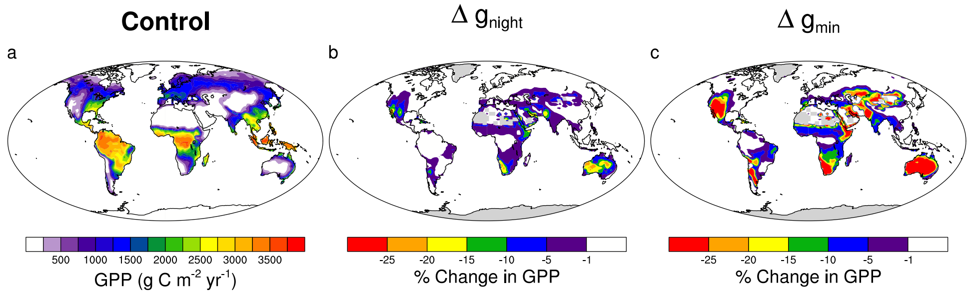
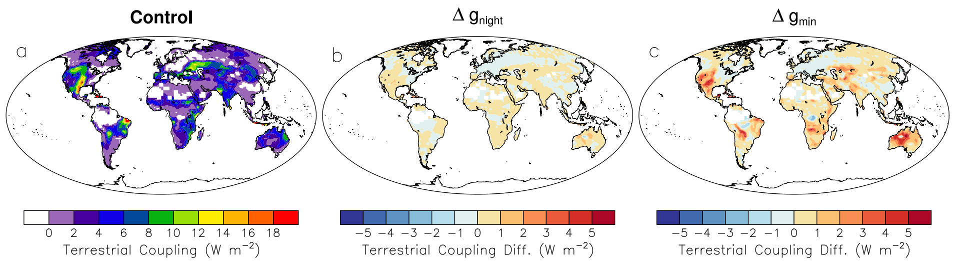

Control
Δ g min
Δ g night
Δ g o
Ethiopia
a
Ethiopia
January
Canopy Conductance (mmol H2O m-2 s-1)
Julian Day
b
Ethiopia
January
Canopy Transpiration (10-6 mm s-1)
Julian Day
c
July
Canopy Conductance (mmol H2O m-2 s-1)
d
July
Canopy Transpiration (10-6 mm s-1)
Day of Year

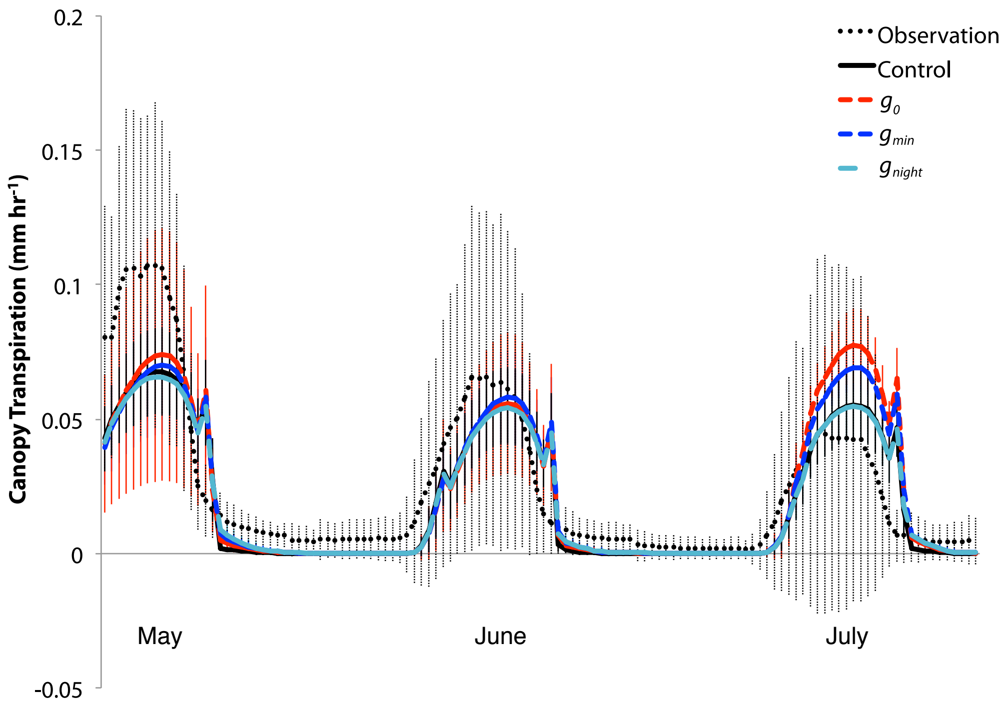

Control
Δgnight
Δgmin
a
b
c
100 200 300 400 500 600 700 800 900
Transpiration (mm H2O yr-1)
1 10 20 30 40 50
% Change in Transpiration
d
e
f
0 200 400 600 800 1000
Runoff (mm yr-1)
-25 -20 -15 -10 -5 -1
% Change in Runoff
g
h
i
0 10 20 30 40 50 60 70 80 90 100
Soil Moisture (%)
-50 -40 -30 -20 -10 -1
% Change in Soil Moisture

614

615


Control
Δ g_night
Δ g_min
a
b
c
500 1000 1500 2000 2500 3000 3500
GPP (g C m-2 yr-1)
-25 -20 -15 -10 -5 -1
% Change in GPP
-25 -20 -15 -10 -5 -1
% Change in GPP


Control
a
0 2 4 6 8 10 12 14 16 18
Terrestrial Coupling (W m^{-2})
Δ g_{night}
b
−5 −4 −3 −2 −1 0 1 2 3 4 5
Terrestrial Coupling Diff. (W m^{-2})
Δ g_{min}
c
−5 −4 −3 −2 −1 0 1 2 3 4 5
Terrestrial Coupling Diff. (W m^{-2})



0.2
0.15
0.1
0.05
0
-0.05
Canopy Transpiration (mm hr-1)
Observation
Control
g0
gmin
gnight
May
June
July

620