

Response to the comments of Anonymous Referee #1 (RC1)

We thank the reviewers and the editor for their suggestions and comments on the manuscript. We have considered all their comments and hope that the revised draft properly addresses their suggestions. Please find our point-by-point replies below (colored in blue). A revised manuscript with tracked changes will be uploaded. Line numbers in our text refer to the no-markup version.

In this paper Li et al., implement the optimality-based stomatal conductance model from Medlyn et al., (2011) (MED) into the FATES dynamic vegetation demography model. They compare the behaviour of this model to the existing empirical Ball-Woodrow-Berry (BWB) model. Firstly they assess how the response of simulated carbon and water fluxes to meteorological drivers (CO₂ concentration, air temperature, radiation, and VPD) differ between the two models to aid in understanding model representation and behaviour. These changes in meteorological drivers are applied in a sensitivity study, and differences arising from model parameterisation versus model structure are explored over a wide range on environmental conditions. Secondly, the authors evaluate the performance of each model at a tropical forest site in Panama. Thirdly the authors explore the application of the soil moisture stress function (the β factor) at different points in the physiological pathway which modifies simulated photosynthesis and stomatal conductance according to available soil moisture. This paper is well written and concise, and provides a nice evaluation of the impact of different representations of stomatal opening on carbon and water fluxes in a dynamic vegetation model, assessing the impact of both model structure and model parameterisation. I believe this paper fits within the scope of GMD and would be of interest to readers. I have a few comments below:

We thank the reviewer for carefully reviewing our submission, providing constructive suggestions, and acknowledging the importance of our work.

Introduction:

- Lines 70 to 80: Please add which models do what with regards to the β factor i.e. which models apply β to g_0 and/or g_1 , and which models apply it to V_{cmax}/J_{max} , or elsewhere in the physiological pathway.

We have included the corresponding model names at Lines 77-85: “To mimic the drought effects on ecosystems, some models have included a soil water stress factor (often denoted as β) which is used to reduce the “base rate” of stomatal model parameters, either g_0 (e.g., CLM, Lawrence et al., 2019), g_1 (e.g., G'DAY, Comins and McMurtrie, 1993; O-CN, Zaehle and Friend, 2010; CABLE, De Kauwe et al., 2015), or both (e.g., ORCHIDEE, Guimberteau et al., 2018). In some cases, it is also used to lower the maximum carboxylation rate of Rubisco (V_{cmax}) (e.g., CLM; O-CN; SIBCASA, Schaefer et al., 2008), both V_{cmax} and the maximum rate of electron transport (J_{max}) (e.g., G'DAY), or directly A (e.g., JULES, Best et al., 2011; Clark et al., 2011). Reductions in A will further reduce g_{sw} . Some models also consider the soil water stress on mesophyll conductance (e.g., SIBCASA; ORCHIDEE)”.

- The authors may find this paper relevant to their discussion on the application of the β factor within land surface models (particularly in the discussion around line 362): “On the Treatment of Soil Water Stress in GCM Simulations of Vegetation Physiology. 2021. Vidale et al., Frontiers in Environmental Science. <https://doi.org/10.3389/fenvs.2021.689301>”.

We thank the reviewer for the suggestion. It's indeed a very relevant paper. We have added the following sentence at Lines 410-412: “To improve models, further systematic evaluation of the β effects on photosynthetic capacity, stomatal conductance and mesophyll conductance in LSMs is highly recommended (Egea et al., 2011; Vidale et al., 2021)”.

Methods:

- Section 2.1: For clarity, can the authors be a bit more explicit about how they implemented the MED scheme, was it as straightforward as replacing equation 1 with equation 2 and adding the β factor?

We have added some additional description at Lines 114-118: “Leaf-level g_{sw} is central to the water, CO_2 and energy cycles in forests. It not only controls the water and CO_2 exchange, but also modifies the energy balance and biochemical processes. Similarly, in FATES, the variable g_{sw} is used to model several processes such as the heat and water transfer and photosynthesis. The calculation of this variable is therefore complex and uses both analytical and numerical solutions to couple the equations describing each process”.

- What is the photosynthesis scheme used to calculate A ?

We added the model description at Lines 104-106: “In FATES, leaf-level photosynthesis (A) in C_3 plants is based on the model of Farquhar et al. (1980) as modified by Collatz et al. (1991). A is calculated as the minimum of RuBP carboxylase (Rubisco) limited rate and RuBP regeneration rate (i.e., the light-limited rate). Net photosynthesis rate (A_{net}) is the difference between A and leaf respiration”.

- Line 110: What measurements are being made at the site to compare with the simulations?

We modified this sentence at Lines 132-134 as: “The Smithsonian Tropical Research Institute canopy crane provides access to the top of the forest canopy and allows us to compare our simulations with previous measurements of stomatal conductance and net photosynthesis rate (Wu et al., 2020; Rogers et al., 2017)”.

- Please add more detail about the model and simulations for clarity. FATES is initialised with real-world forest inventory data – so for these simulations that are at a single study site what does that represent – a single tree, an area of forest? Later on PFT specific parameterisations for the g_1 parameter are used, so are there different PFTs each with their own cohort structure? What meteorological forcing is required to drive the model, at what temporal resolution? Is the driving data provided by the test site, or from elsewhere? How is LAI modeled? A bit more clarity on the model and how it is run is required for those not familiar with FATES or CLM.

The inventory data has information of tree size distribution for the whole forest area. For simplicity, in our FATES simulations we assumed that the site is populated entirely by the broadleaf evergreen tropical (BET) tree plant functional type. We parameterized g_1 based on measurements of eight different species which all belong to BET tree category. The FATES model is driven by half-hourly longwave radiation, shortwave radiation, air temperature, specific humidity, precipitation, surface pressure, wind speed, and atmospheric CO_2 concentration. The synthetic climate forcing for the sensitivity runs was created by ourself, while that for evaluation against in situ measurements was adopted from the meteorological station at the site (Faybishenko et al., 2019). The leaf area of each cohort is calculated from leaf biomass and specific leaf area. Leaf biomass is controlled by the processes of phenology, allocation and turnover. Specific leaf area is a PFT-specific parameter. We clarified those points in the revised manuscript at Lines 140-141, 143-145, 180-181, 158-159, 197-199, and 109-111.

Results:

- What causes the difference between MED and BWB in VPD response when $VPD > 1.5kPa$? What do observations suggest is a more realistic response? Are there any observations from this site for the tropical trees to try and help pin down how A and g_s are responding?

The difference between MED and BWB in VPD response when $VPD > 1.5kPa$ is caused by the different formulation of humidity in the two models. g_{sw} simulated by the power function of MED model decreases hyperbolically while that simulated by the linear function of BWB model drops steeply. The nonlinear response of g_{sw} to VPD when using MED model is supported by some observations (Marchin et al., 2016; Hérault et al., 2013; Wang et al., 2009; Domingues et al., 2014). Rising global temperature will raise the VPD but not the RH and therefore a formulation, such as the Medlyn model, may be better able to capture the response of vegetation to future global change (Way et al., 2011; Katul et al., 2009; Rogers et al., 2017b). It is very challenging to control the ambient temperature when studying the response of g_{sw} to relative humidity and we did not have any observations from this site about the response to relative humidity.

We added some of the above discussion at Lines 368-372: “ g_{sw} simulated by the power function of the MED model decreases hyperbolically while that simulated by the linear function of the BWB model drops steeply. The nonlinear response of g_{sw} to VPD_a when using the MED model is supported by some observations (Marchin et al., 2016; Hérault et al., 2013; Wang et al., 2009; Domingues et al., 2014), but more measurements of leaf-level VPD_a responses would be valuable”.

- Why is there a bigger difference (comparing MED-B and MED-default) in simulated g_s compared to A ?

The difference in g_1 directly influences the magnitude of g_{sw} , causing the significant divergence in g_{sw} . However, it propagates to the simulation of intracellular CO_2 first and finally to A , which is the minimum root of quadratic equation of co-limitation rates from Rubisco limited and RuBP limited photosynthesis rates. Similar patterns are also discerned for ET and GPP, in which other factors such as VPD and leaf area index take effect, attenuating the difference caused by g_1 .

We added the above discussion at Lines 364-366: “However, different g_1 values did not markedly change the magnitudes of A_{net} and GPP, suggesting that the difference of g_1 propagates to the simulation of intercellular CO_2 first and finally to A_{net} with attenuated effects”.

- Why does simulated ET increase with increasing VPD when g_s decreases?

ET can be approximately represented as $ET = g_{sw} \times VPD$, where g_{sw} can be expressed as $\frac{f(A, CO_2)}{\sqrt{VPD}}$ for the Medlyn model. Therefore, ET is roughly proportional to \sqrt{VPD} . As a result, simulated ET increases with increasing VPD.

- Line 255: Can you explain the abrupt changes better – I don’t really see that MED is behaving that differently to BWB, and VPD rarely gets as low as 0.1 kPa.

We agree that the difference is not clear. So we have deleted this sentence to prevent confusion in the revised manuscript.

- Could Figs 5, 6, 7 and 8 be condensed? I wonder whether the diurnal cycles for the days without measurements are necessary? The months could then be plotted side by side for easier comparison (and on the same scale for the Met vars to make it easier to see how conditions change by month as the dry season progresses)?

We agree that the modeling results for the days without measurements are not very necessary for the evaluation purpose. We also adopted the suggestion to plot all evaluation results together into Fig. 5. For the dry day in April, the climate drivers did not exhibit distinct trends compared with other months, but the soil moisture content was quite low (see Fig. 6). To be consistent, we also modified Fig. 7 to only include results with corresponding measurements.

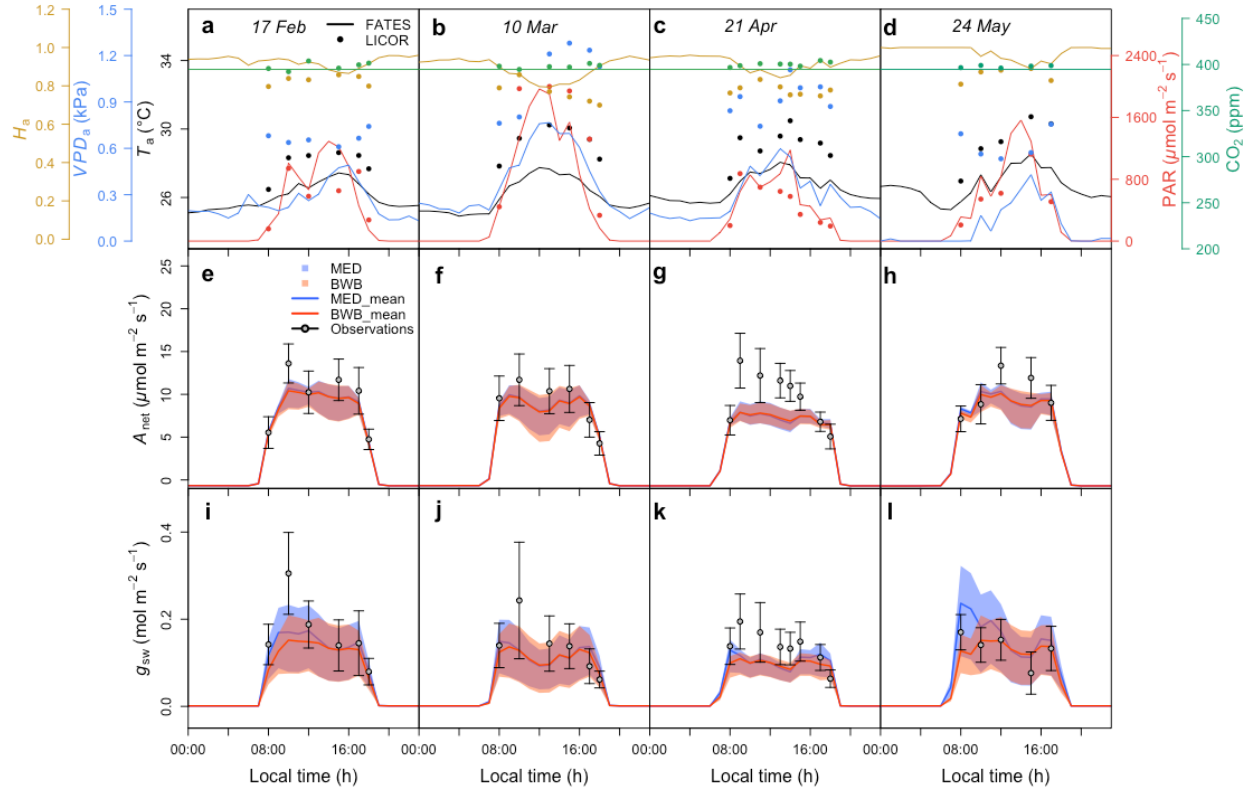


Fig. 5. (a-d) Diurnal change in climate forcing, (e-h) model-data comparison of net photosynthesis rate (A_{net}), (i-l) model-data comparison of stomatal conductance (g_{sw}) for four field campaign dates. In panel (a-d), lines and filled points represent climate forcing data used in FATES and in situ measurements, respectively. Different colors are for different types, black for T_a , red for PAR, blue for VPD_a , green for atmospheric CO_2 concentration, and gold for H_a . In panel (e-l) shading areas represent range of FATES model ensemble results with different measured g_1 values for different species, while lines represent the averages of these ensemble results. Blue shading areas and lines are for results from the MED model, and red for the BWB model. Gray filled circles for the measured data represent averages across species. Black error bars for the measured data represent the 95 % CI across species. Columns correspond to days of measurements and are presented in chronological order for 17 February, 10 March, 21 April, and 24 May.

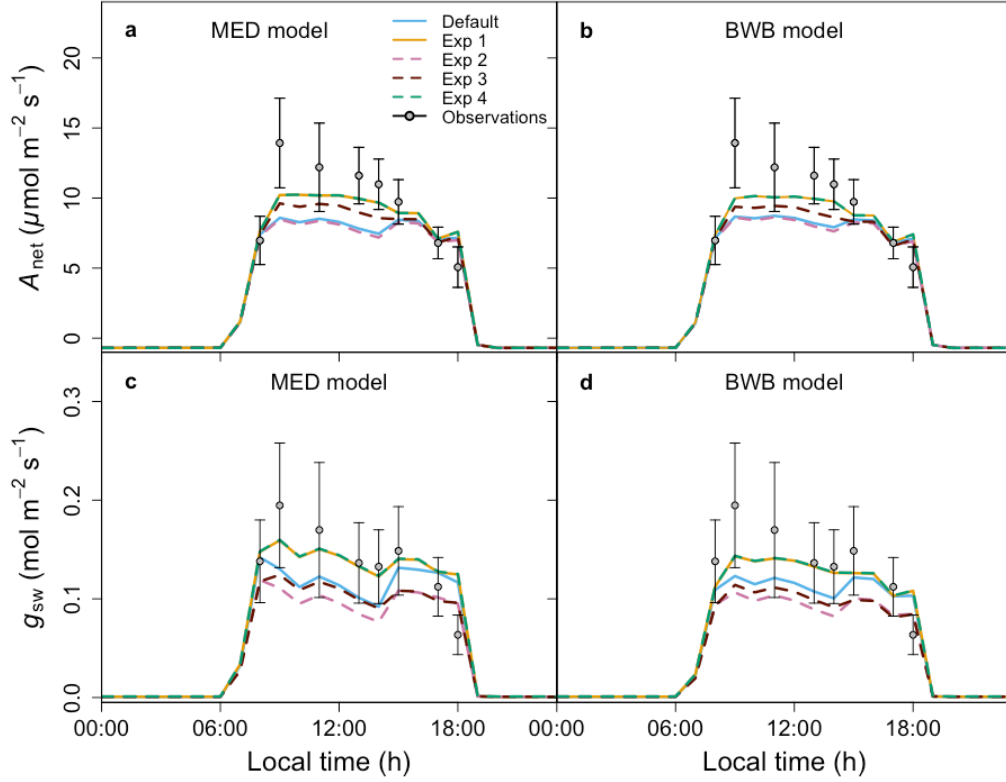


Fig. 7. Comparison between the model outputs and measurements on 21 April 2016 for (a) the MED model net photosynthesis (A_{net}), (b) the BWB model A_{net} , (c) the MED model stomatal conductance (g_{sw}), and (d) the BWB model g_{sw} with different soil water stress effects on parameters in FATES (Table 3).

- Are there any observations of soil moisture at the site? In April it seems that although the model is simulating reduced soil moisture availability which depresses A and g_s , the measured A and g_s remain as high as in other months. Could it not be that the simulation of soil moisture stress itself in the model is not right and more of an issue than where the β factor is applied? How are soil parameters set in the model? Are these informed by the site-level information?

We thank the reviewer for prompting us to explore this further and feel the addition of the new figures and discussion markedly improve the manuscript. Soil water stress is a function of soil water content and parameters related to plant response, root distribution and soil properties. We added information about the stress factor at Lines 123-127: “The soil wilting factor is a bounded linear function of soil matric potential, defined by two parameters, the soil water potential at (and above) which stomata are fully open, and the value at which stomata are fully closed. The soil matric potential is related to the soil water content, soil texture, and organic matter content. The root fraction is determined by PFT-specific root distribution parameters”.

Due to the lack of in situ parameters, we only used general soil and root parameters in the simulations. We compared the modeled soil water contents against soil moisture products of ECMWF Reanalysis data version 5 (ERA5) (Hersbach et al., 2018) for the site. Results show that the model captured the dynamics and approximate magnitude of the average soil water content (Fig. 6). Similar patterns were observed for different layers throughout the first three meters of the soil column (Fig. S3). Although soil moisture was relatively well simulated, root fraction and other soil properties were difficult to constrain due to scarce observations. The relatively large mismatch of modeled and measured A_{net} and g_{sw} in April compared with other months is likely to be related to soil water stress as we have ruled out the influence from other climate factors (Fig. 5). Our results indicate that the simulations that treated the stress factor as one (i.e., no stress) for all parameters produced higher A_{net} and g_{sw} and matched the observations best. This suggests the photosynthesis and stomatal conductance in tropical forests are more resilient to drought than are currently represented by FATES.

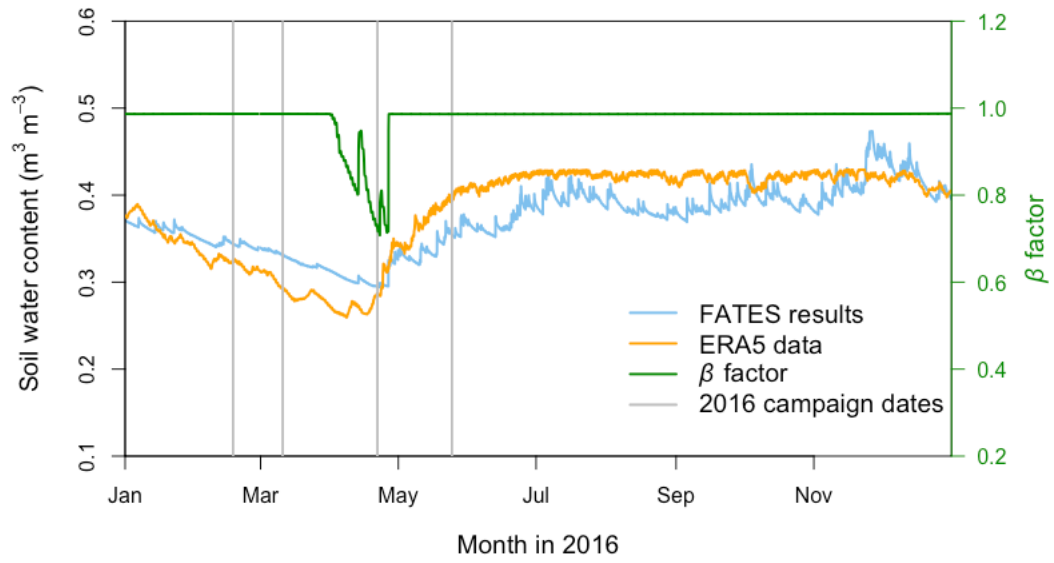


Fig.6. Annual cycle of modeled volumetric soil water content (blue line) and corresponding soil water stress (β) factor (green line) from FATES simulation, and ERA5 reanalysis soil water content data (orange line) at the San Lorenzo field site in 2016. The soil water content data are means across all soil layers. For the β factor, “1” represents fully saturated soil, while “0” represents very dry soil. Vertical gray lines indicate the four campaign dates in 2016.

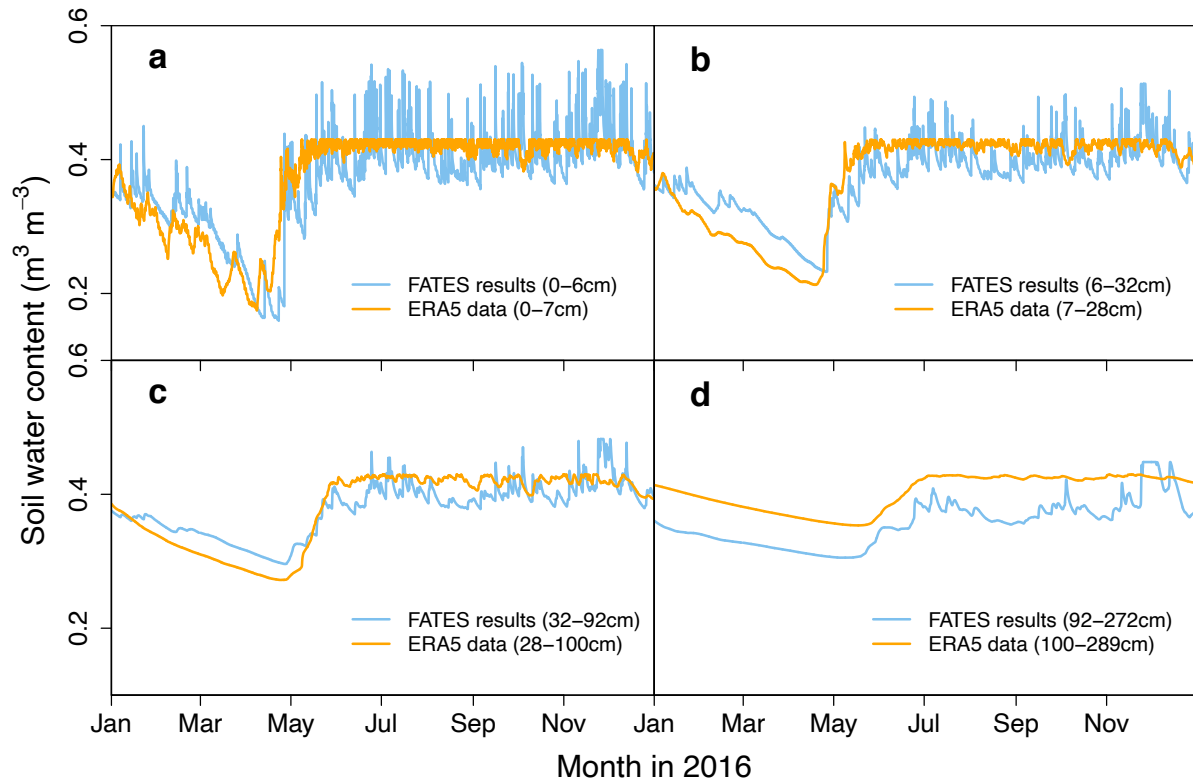


Fig. S3. Annual cycle of modeled soil water content (blue lines) and corresponding ERA5 reanalysis data (orange lines) for different soil layers.

We added the first figure above to the revised manuscript (Fig. 6) and the second to the supplemental material (Fig. S3). Besides, we added some texts in the Methods at Lines 205-208 as:

“However, whether the calculation of the β factor can truly reflect soil water conditions is unclear. To the best of our knowledge, the relevance of the β factor has not been rigorously tested for tropical ecosystems, in comparison with measured g_{sw} and A_{net} , either. We therefore first compared the modeled soil water content and β factor against soil moisture products of ECMWF Reanalysis data version 5 (ERA5) (Hersbach et al., 2018)”.

Corresponding results were added at Lines 305-309 as:

“Compared with the ERA5 soil moisture products, FATES generally captured the magnitude and trend of the observed average soil water content at the San Lorenzo site (Fig. 6). FATES also simulated the soil water content well for different layers of the soil column (Fig. S3). By April 2016, at the peak of the dry season in a dry year, the simulated soil moisture stress factor (averaged over all the soil layers) reached an annual minimum (0.7), corresponding to the observed soil moisture drying trend (Fig. 6)”.

We also added some discussion at Lines 400-410 as:

“Despite previous extensive experimental studies of the β effects on plant physiological parameters, understanding of the results of applying β effects in models is still inadequate. The uncertainty of the β calculation is a major challenge. Based on the equations, the β factor is a function of soil water content, modified by parameters related to plant response, root distribution, and soil properties. Due to the lack of in situ measurements, we only used general parameters for the β factor in the simulations. Although soil moisture content was relatively well simulated (Fig. 6), root fraction and other soil properties were difficult to constrain due to scarce observations. In our study, by toggling on and off the β effects on stomatal and photosynthetic parameters, we were able to learn more about how the calculation of β influences model outputs. Overall, we found that the predictions of g_{sw} and A_{net} were closer to the measurements when the β factor was treated as one (i.e., no stress). Similar studies also found that the implementation of the β factor in CLM overestimated the drought-related productivity loss compared with the observations, biased the transpiration rate, or lacked diurnal variability (Powell et al., 2013; Kennedy et al., 2019; Bonan et al., 2014)”.

Discussion:

- Line 320 onwards: I am unclear on the third point. It says the response curves of A_{net} and g_s are directly comparable to the leaf-level gas exchange measurements, but these data are not shown anywhere and do not seem to be used in this evaluation. These indeed would be invaluable to help determine which model behaviour is more realistic, for example to help pin down the VPD response which is largely where the two models seem to diverge. If they are available could they be included?

We agree that such data would be really useful, but we did not measure the corresponding leaf-level response curves. The value of this synthetic approach is being able to observe how the model simulates theoretical responses to environmental variables that are well understood by physiologists and ensure that expected behaviors are reproduced e.g., a temperature optimum. The focus in this study was to understand model differences in terms of model response to key climate forcing (as at Lines 97-99).

We made this point clearer in the revised manuscript at Lines 352-354: “Third, understanding model response to synthetic climate forcing (Fig. 1-4) is a powerful diagnostic tool because the model outputs can be evaluated in comparison to known and measurable physiological responses to environmental variation, such as radiation and CO_2 ”.

- Some discussion around the g_0 parameter would be interesting. Studies have shown that the g_0 term affects predictions of g_s at all times, not just when A is close to zero, making predictions of plant water use very sensitive to this parameter. Is it right to have a minimum conductance when A_{net} is zero? What are the authors' justification for including the g_0 term in the MED formulation? Did the authors look at sensitivity of simulated g_s/A_{net} to g_0 ?

We appreciate the reviewer's comments and agree that the value of g_0 should be given attention. There is less consensus for the parameterization of g_0 due to different definitions and measurements of this parameter. Whether g_0 should be an intercept from data fitting, a minimum threshold when A_{net} approaches zero, a night time g_{sw} , or the cuticular conductance is still an active research topic (Lombardozzi et al., 2017; Duursma et al., 2019; Lamour et al., 2022). The slope parameter g_1 we used in the model was from Lin et al. (2015), estimated with the assumption that g_0 was zero. In our implementation, we not only included a non-zero g_0 in the numerical calculation of g_{sw} , but also set a small positive value for g_0 to prevent g_{sw} to become zero or negative when A_{net} approaches zero or negative. In this way, the leaf stomatal resistance (i.e., the reverse of g_{sw}) will not become infinite during the simulations. Besides, including a user-defined g_0 in the equation will also encourage further exploration about the different usage of g_0 . For example, some studies find g_0 was related to soil water condition (Misson et al., 2004) or heatwave (Duarte et al., 2016).

To address the reviewer's comments further, we tested the sensitivity of g_{sw} , A_{net} , ET and GPP to different g_0 with our synthetic climate forcing. In addition to the simulations with our default value ($1000 \mu\text{mol m}^{-2} \text{s}^{-1}$), the g_0 was set zero or the commonly adopted value of $10000 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Sellers et al. 1996). Results showed that compared with a zero g_0 , the default g_0 had almost no influence on the model response of g_{sw} . Using the ten-fold larger estimate for g_0 ($10000 \mu\text{mol m}^{-2} \text{s}^{-1}$) only resulted in a small effect on the magnitudes of g_{sw} , A_{net} , ET, and GPP (Fig. S5-S8).

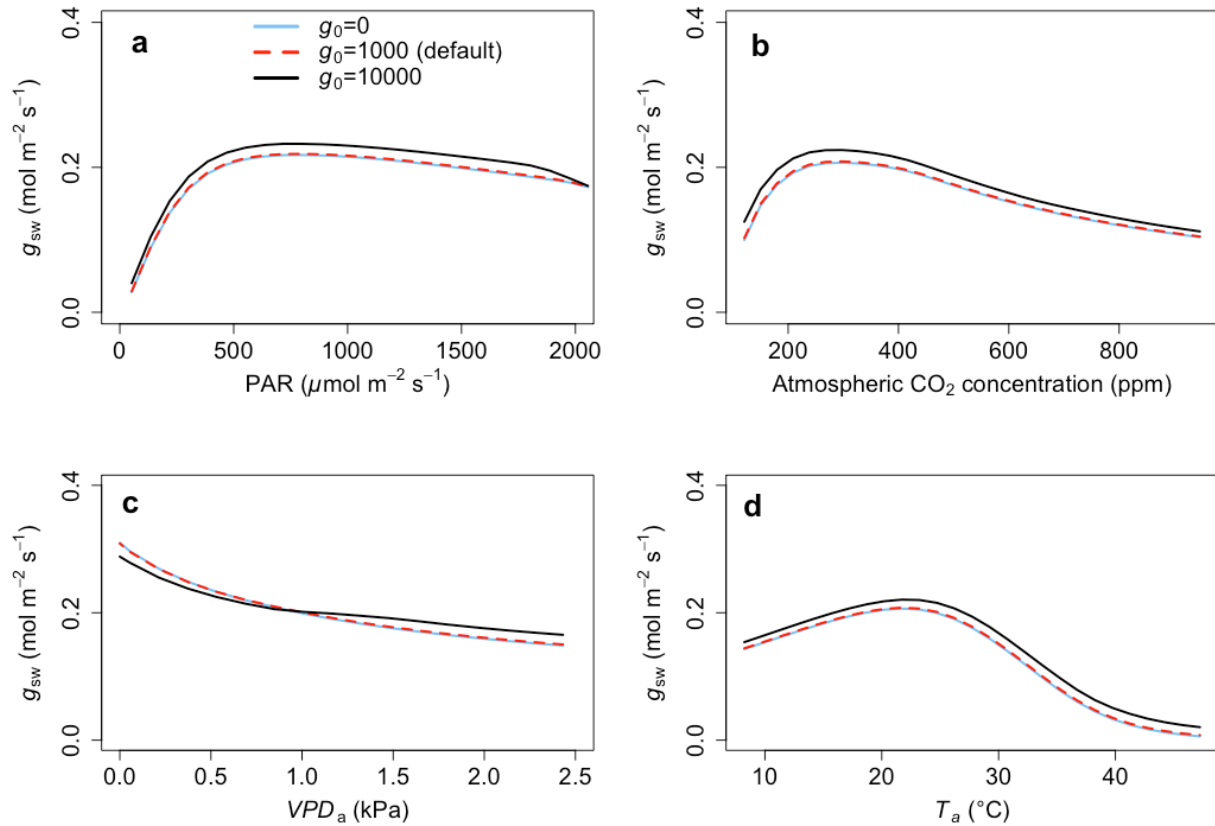


Fig. S5. The responses of stomatal conductance (g_{sw}) to scenarios (a) Radiation, (b) CO_2 , (c) VPD_a , and (d) T_a for the three MED model setups with different g_0 values. g_0 is in $\mu\text{mol m}^{-2} \text{s}^{-1}$.

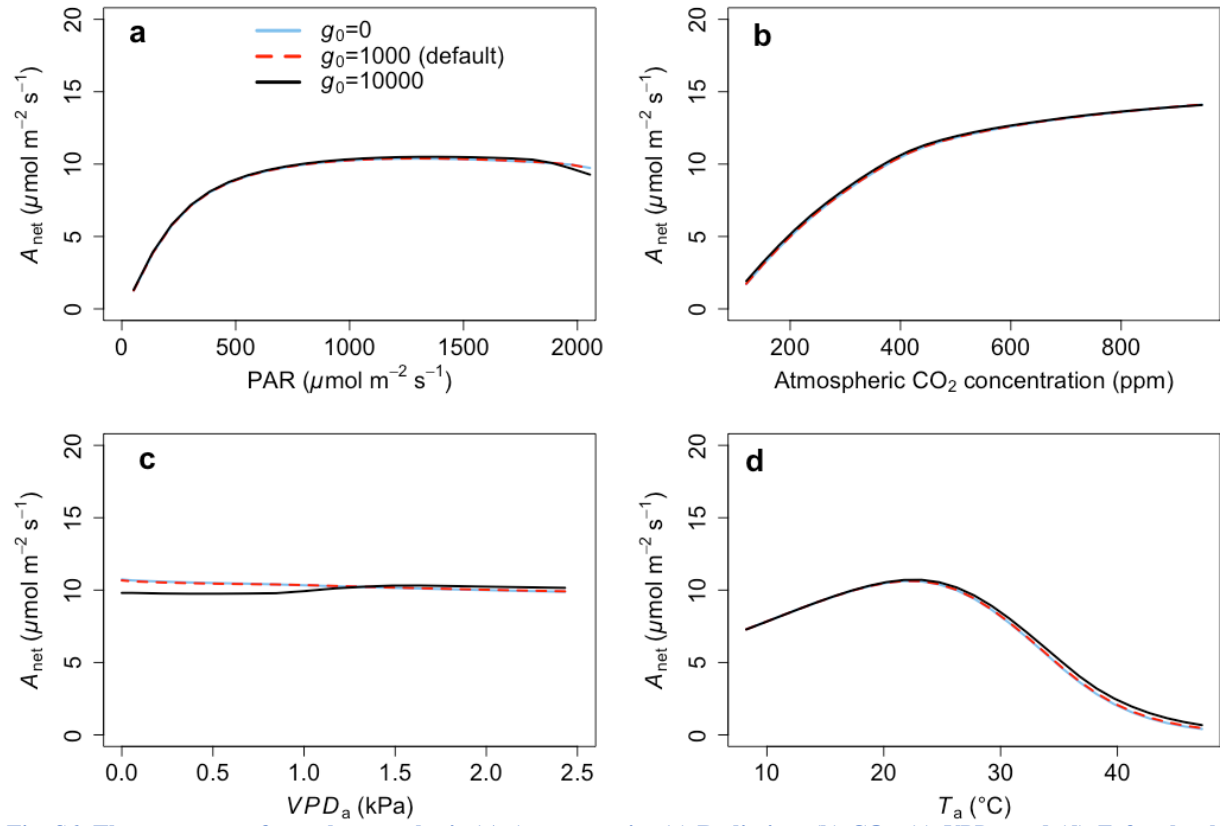


Fig. S6. The responses of net photosynthesis (A_{net}) to scenarios (a) Radiation, (b) CO₂, (c) VPD_a, and (d) T_a for the three MED model setups with different g_0 values. g_0 is in $\mu\text{mol m}^{-2} \text{s}^{-1}$.

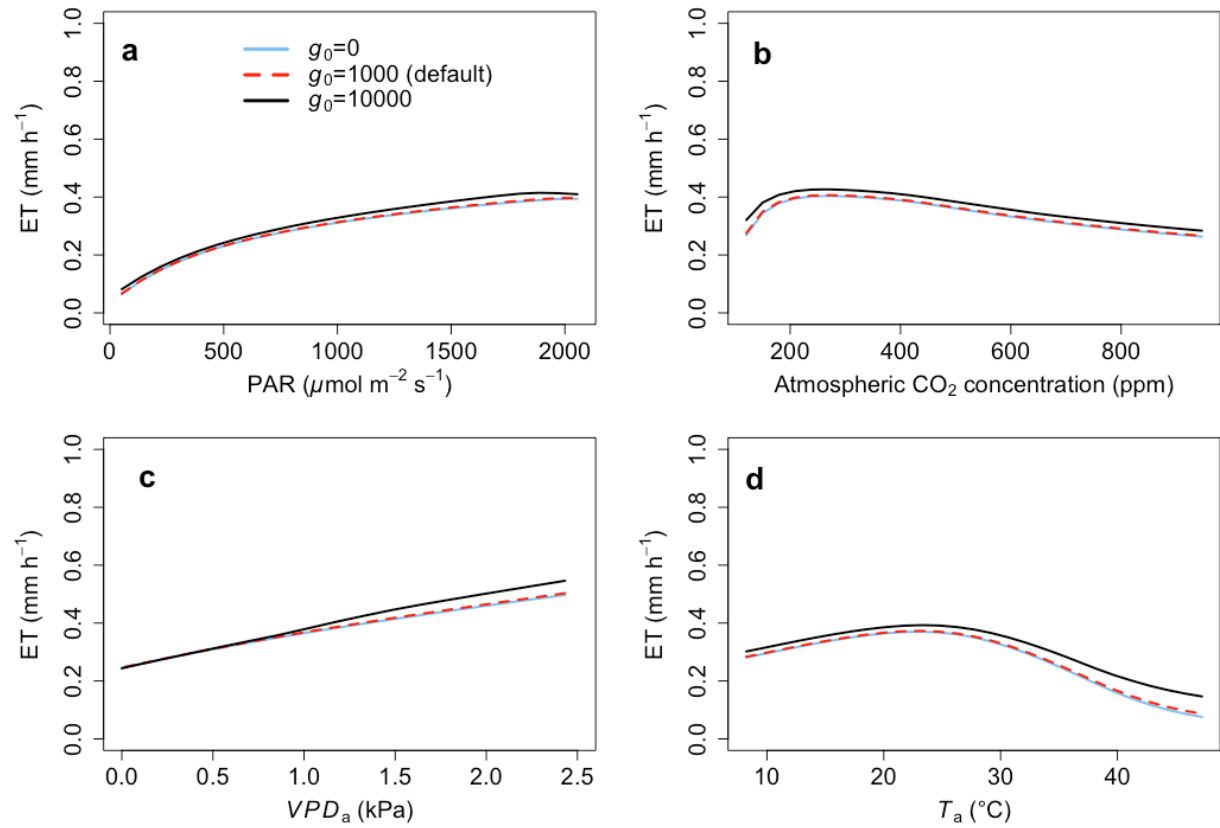


Fig. S7. The responses of evapotranspiration (ET) to scenarios (a) Radiation, (b) CO₂, (c) VPD_a, and (d) T_a for the three MED model setups with different g_0 values. g_0 is in $\mu\text{mol m}^{-2} \text{s}^{-1}$.

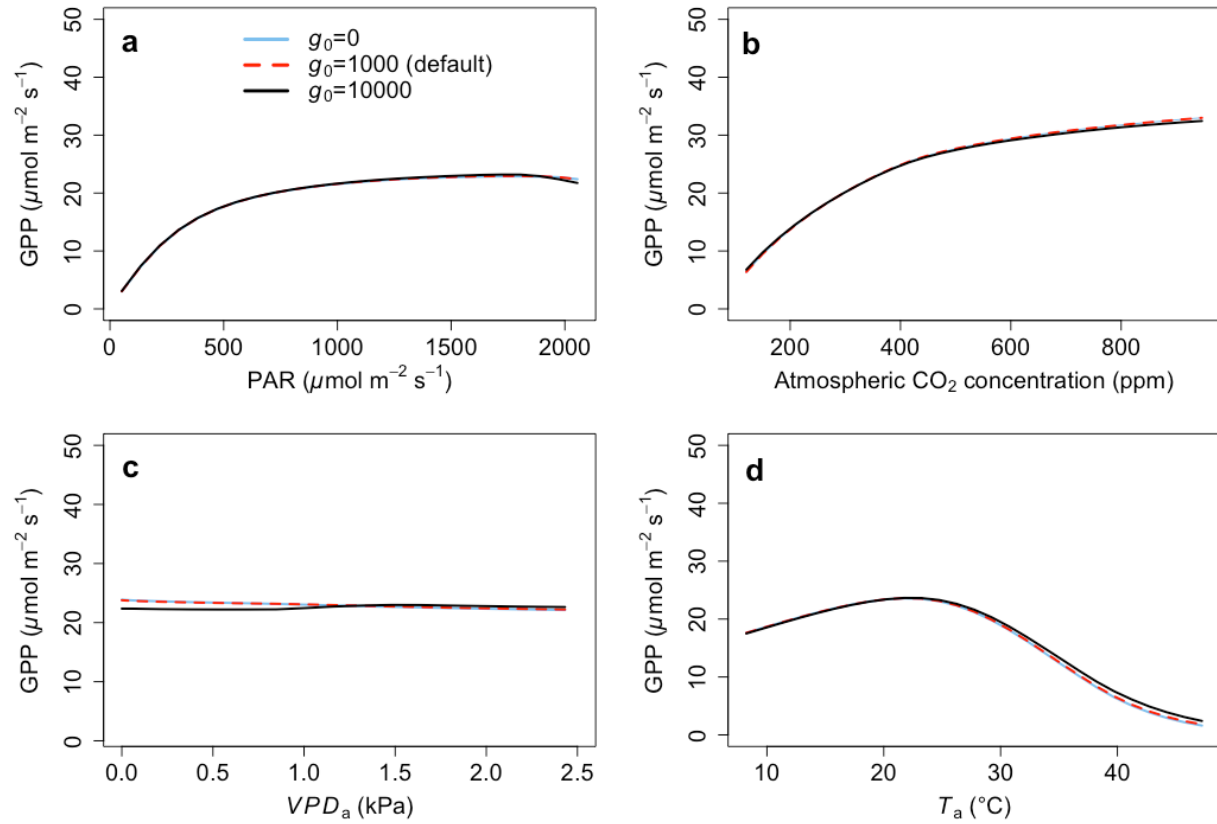


Fig. S8. The gross primary productivity (GPP) to scenarios (a) Radiation, (b) CO₂, (c) VPD_a , and (d) T_a for the three MED model setups with different g_0 values. g_0 is in $\mu\text{mol m}^{-2} \text{s}^{-1}$.

We have added the above figures to the supplemental material (Fig. S5-S8) and one paragraph at Lines 433–446 as: “Parameterization of g_0 has been shown critical for predicting ecosystem fluxes (De Kauwe et al., 2015; Barnard and Bauerle, 2013). However, there is little agreement on how to parameterize g_0 due to different definitions and measurement approaches for this parameter. Whether g_0 should be an intercept from data fitting, a minimum threshold when A_{net} approaches zero, a night time g_{sw} , or the cuticular conductance is still an active research topic (Lombardozzi et al., 2017; Duursma et al., 2019; Lamour et al., 2022; Davidson et al., 2022). The slope parameter g_1 we used in the model was from Lin et al. (2015), estimated with the assumption that g_0 was zero. In our implementation, we not only included a non-zero g_0 in the numerical calculation of g_{sw} , but also set a small positive value for g_0 to prevent g_{sw} becoming zero or negative when A_{net} approaches zero. In this way, the leaf stomatal resistance (i.e., the reverse of g_{sw}) will not become infinite during the simulations. To understand how different g_0 values influence g_{sw} and A_{net} , we tested the sensitivity of g_{sw} , A_{net} , ET, and GPP to different g_0 values with our synthetic climate forcing listed in Table 2. In addition to the simulations with our default value ($1000 \mu\text{mol m}^{-2} \text{s}^{-1}$), the g_0 was set zero or the commonly adopted value of $10000 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Sellers et al. 1996). A comparison of $g_0=0$ and $g_0=1000 \mu\text{mol mol}^{-1}$ showed a very minor effect on the model response of g_{sw} . Using the ten-fold larger estimate for g_0 ($10000 \mu\text{mol mol}^{-1}$) only resulted in a small effect on the magnitudes of g_{sw} , A_{net} , ET, and GPP (Fig. S5-S8)”.

References

Barnard, D. M. and Bauerle, W. L.: The implications of minimum stomatal conductance on modeling water flux in forest canopies, *J. Geophys. Res. Biogeosciences*, 118, 1322–1333, <https://doi.org/10.1002/jgrg.20112>, 2013.

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

Bonan, G. B., Williams, M., Fisher, R. A., and Oleson, K. W.: Modeling stomatal conductance in the earth system: Linking leaf water-use efficiency and water transport along the soil-plant-atmosphere continuum, *Geosci. Model Dev.*, 7, 2193–2222, <https://doi.org/10.5194/gmd-7-2193-2014>, 2014.

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, *Geosci. Model Dev.*, 4, 701–722, <https://doi.org/10.5194/gmd-4-701-2011>, 2011.

Collatz, G. J., Ball, J. T., Grivet, C., and Berry, J. A.: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer, *Agric. For. Meteorol.*, 54, 107–136, [https://doi.org/10.1016/0168-1923\(91\)90002-8](https://doi.org/10.1016/0168-1923(91)90002-8), 1991.

Comins, H. N. and McMurtrie, R. E.: Long-Term Response of Nutrient-Limited Forests to CO₂ Enrichment; Equilibrium Behavior of Plant-Soil Models, *Ecol. Appl. Publ. Ecol. Soc. Am.*, 3, 666–681, <https://doi.org/10.2307/1942099>, 1993.

Davidson, K. J., Lamour, J., Rogers, A., and Serbin, S. P.: Late-day measurement of excised branches results in uncertainty in the estimation of two stomatal parameters derived from response curves in *Populus deltoides* Bartr. × *Populus nigra* L., *Tree Physiol.*, tpac006, <https://doi.org/10.1093/treephys/tpac006>, 2022.

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

Domingues, T. F., Martinelli, L. A., and Ehleringer, J. R.: Seasonal patterns of leaf-level photosynthetic gas exchange in an eastern Amazonian rain forest, *Plant Ecol. Divers.*, 7, 189–203, <https://doi.org/10.1080/17550874.2012.748849>, 2014.

Duarte, A. G., Katata, G., Hoshika, Y., Hossain, M., Kreuzwieser, J., Arneth, A., and Ruehr, N. K.: Immediate and potential long-term effects of consecutive heat waves on the photosynthetic performance and water balance in Douglas-fir, *J. Plant Physiol.*, 205, 57–66, <https://doi.org/10.1016/j.jplph.2016.08.012>, 2016.

Duursma, R. A., Blackman, C. J., López, R., Martin-StPaul, N. K., Cochard, H., and Medlyn, B. E.: On the minimum leaf conductance: its role in models of plant water use, and ecological and environmental controls, *New Phytol.*, 221, 693–705, <https://doi.org/10.1111/nph.15395>, 2019.

Egea, G., Verhoef, A., and Vidale, P. L.: Towards an improved and more flexible representation of water stress in coupled photosynthesis–stomatal conductance models, *Agric. For. Meteorol.*, 151, 1370–1384, <https://doi.org/10.1016/j.agrformet.2011.05.019>, 2011.

Farquhar, G. D., von Caemmerer, S., and Berry, J. A.: A biochemical model of photosynthetic CO₂ assimilation in leaves of C₃ species, *Planta*, 149, 78–90, <https://doi.org/10.1007/BF00386231>, 1980.

Faybishenko, B., Paton, S., Knox, R., Varadharajan, C., Agarwal, D., and Powell, T.: San Lorenzo meteorological drivers, Next-Generation Ecosystem Experiments Tropics; STRI; Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States), <https://doi.org/10.15486/ngt/1507769>, 2019.

Guimberteau, M., Zhu, D., Maignan, F., Huang, Y., Yue, C., Dantec-Nédélec, S., Ottlé, C., Jornet-Puig, A., Bastos, A., Laurent, P., Goll, D., Bowring, S., Chang, J., Guenet, B., Tifafi, M., Peng, S., Krinner, G., Ducharne, A., Wang,

- F., Wang, T., Wang, X., Wang, Y., Yin, Z., Lauerwald, R., Joetzjer, E., Qiu, C., Kim, H., and Ciais, P.: ORCHIDEE-MICT (v8.4.1), a land surface model for the high latitudes: model description and validation, *Geosci. Model Dev.*, 11, 121–163, <https://doi.org/10.5194/gmd-11-121-2018>, 2018.
- Hérault, A., Lin, Y. S., Bourne, A., Medlyn, B. E., and Ellsworth, D. S.: Optimal stomatal conductance in relation to photosynthesis in climatically contrasting Eucalyptus species under drought, *Plant Cell Environ.*, 36, 262–274, <https://doi.org/10.1111/j.1365-3040.2012.02570.x>, 2013.
- Hersbach, H., de Rosnay, P., Bell, B., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Alonso-Balmaseda, M., Balsamo, G., Bechtold, P., Berrisford, P., Bidlot, J.-R., de Boissésou, E., Bonavita, M., Browne, P., Buizza, R., Dahlgren, P., Dee, D., Dragani, R., Diamantakis, M., Flemming, J., Forbes, R., Geer, A., Haiden, T., Hólm, E., Haimberger, L., Hogan, R., Horányi, A., Janiskova, M., Laloyaux, P., Lopez, P., Munoz-Sabater, J., Peubey, C., Radu, R., Richardson, D., Thépaut, J.-N., Vitart, F., Yang, X., Zsótér, E., and Zuo, H.: Operational global reanalysis: progress, future directions and synergies with NWP, ERA Report Series, 2018.
- Katul, G. G., Palmroth, S., and Oren, R.: Leaf stomatal responses to vapour pressure deficit under current and CO₂-enriched atmosphere explained by the economics of gas exchange, *Plant Cell Amp Environ.*, 32, 968–979, 2009.
- Kennedy, D., Swenson, S., Oleson, K. W., Lawrence, D. M., Fisher, R., Lola da Costa, A. C., and Gentine, P.: Implementing Plant Hydraulics in the Community Land Model, Version 5, *J. Adv. Model. Earth Syst.*, 11, 485–513, <https://doi.org/10.1029/2018MS001500>, 2019.
- Lamour, J., Davidson, K. J., Ely, K. S., Le Moguédec, G., Leakey, A. D. B., Li, Q., Serbin, S. P., and Rogers, A.: An improved representation of the relationship between photosynthesis and stomatal conductance leads to more stable estimation of conductance parameters and improves the goodness-of-fit across diverse data sets, *Glob. Change Biol.*, n/a, <https://doi.org/10.1111/gcb.16103>, 2022.
- Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., Van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., Wieder, W. R., Xu, C., Ali, A. A., Badger, A. M., Bisht, G., Van Den Broeke, M., Brunke, M. A., Burns, S. P., Buzan, J., Clark, M., Craig, A., Dahlin, K., Drewniak, B., Fisher, J. B., Flanner, M., Fox, A. M., Gentine, P., Hoffman, F., Keppel-Aleks, G., Knox, R., Kumar, S., Lenaerts, J., Leung, L. R., Lipscomb, W. H., Lu, Y., Pandey, A., Pelletier, J. D., Perket, J., Randerson, J. T., Ricciuto, D. M., Sanderson, B. M., Slater, A., Subin, Z. M., Tang, J., Thomas, R. Q., Martin, M. V., Zeng, X., Lawrence, D. M., Fisher, R. A., Koven, C. D., Swenson, K. W., and Lawrence, A. L.: The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty Special Section: Community Earth System Model version 2 (CESM2) Special Collection Citation, <https://doi.org/10.1029/2018MS001583>, 2019.
- Lin, Y. S., Medlyn, B. E., Duursma, R. A., Prentice, I. C., Wang, H., Baig, S., Eamus, D., De Dios, V. R., Mitchell, P., Ellsworth, D. S., De Beeck, M. O., Wallin, G., Uddling, J., Tarvainen, L., Linderson, M. L., Cernusak, L. A., Nippert, J. B., Ocheltree, T. W., Tissue, D. T., Martin-StPaul, N. K., Rogers, A., Warren, J. M., De Angelis, P., Hikosaka, K., Han, Q., Onoda, Y., Gimeno, T. E., Barton, C. V. M., Bennie, J., Bonal, D., Bosc, A., Löw, M., Macinins-Ng, C., Rey, A., Rowland, L., Setterfield, S. A., Tausz-Posch, S., Zaragoza-Castells, J., Broadmeadow, M. S. J., Drake, J. E., Freeman, M., Ghannoum, O., Hutley, L. B., Kelly, J. W., Kikuzawa, K., Kolari, P., Koyama, K., Limousin, J. M., Meir, P., Da Costa, A. C. L., Mikkelsen, T. N., Salinas, N., Sun, W., and Wingate, L.: Optimal stomatal behaviour around the world, *Nat. Clim. Change*, 5, 459–464, <https://doi.org/10.1038/nclimate2550>, 2015.
- Lombardozzi, D. L., Zeppel, M. J. B., Fisher, R. A., and Tawfik, A.: Representing nighttime and minimum conductance in CLM4.5: global hydrology and carbon sensitivity analysis using observational constraints, *Geosci. Model Dev.*, 10, 321–331, <https://doi.org/10.5194/gmd-10-321-2017>, 2017.
- Marchin, R. M., Broadhead, A. A., Bostic, L. E., Dunn, R. R., and Hoffmann, W. A.: Stomatal acclimation to vapour pressure deficit doubles transpiration of small tree seedlings with warming: Stomatal acclimation increases transpiration, *Plant Cell Environ.*, 39, 2221–2234, <https://doi.org/10.1111/pce.12790>, 2016.

Misson, L., Panek, J. A., and Goldstein, A. H.: A comparison of three approaches to modeling leaf gas exchange in annually drought-stressed ponderosa pine forests, *Tree Physiol.*, 24, 529–541, <https://doi.org/10.1093/treephys/24.5.529>, 2004.

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

Rogers, A., Serbin, S., Ely, K., Wu, J., Wolfe, B., Dickman, T., Collins, A., Detto, M., Grossiord, C., McDowell, N., and Michaletz, S.: Diurnal leaf gas exchange survey, Feb2016-May2016, PA-SLZ, PA-PNM: Panama, <https://doi.org/10.15486/NGT/1411972>, 2017.

Schaefer, K., Collatz, G. J., Tans, P., Denning, A. S., Baker, I., Berry, J., Prihodko, L., Suits, N., and Philpott, A.: Combined Simple Biosphere/Carnegie-Ames-Stanford Approach terrestrial carbon cycle model, *J. Geophys. Res. Biogeosciences*, 113, <https://doi.org/10.1029/2007JG000603>, 2008.

Sellers, P. J., Randall, D. A., Collatz, G. J., Berry, J. A., Field, C. B., Dazlich, D. A., Zhang, C., Collelo, G. D., and Bounoua, L.: A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation, *J. Clim.*, 9, 676–705, 1996.

Vidale, P. L., Egea, G., McGuire, P. C., Todt, M., Peters, W., Müller, O., Balan-Sarojini, B., and Verhoef, A.: On the Treatment of Soil Water Stress in GCM Simulations of Vegetation Physiology, *Front. Environ. Sci.*, 9, 2021.

Wang, S., Yang, Y., Trishchenko, A. P., Barr, A. G., Black, T. A., and Mccaughey, H.: Modeling the response of canopy stomatal conductance to humidity, *J. Hydrometeorol.*, 10, 521–532, <https://doi.org/10.1175/2008JHM1050.1>, 2009.

Way, D. A., Oren, R., Kim, H.-S., and Katul, G. G.: How well do stomatal conductance models perform on closing plant carbon budgets? A test using seedlings grown under current and elevated air temperatures, *J. Geophys. Res. Biogeosciences*, 116, <https://doi.org/10.1029/2011JG001808>, 2011.

Wu, J., Serbin, S. P., Ely, K. S., Wolfe, B. T., Dickman, L. T., Grossiord, C., Michaletz, S. T., Collins, A. D., Detto, M., McDowell, N. G., Wright, S. J., and Rogers, A.: The response of stomatal conductance to seasonal drought in tropical forests, *Glob. Change Biol.*, 26, 823–839, <https://doi.org/10.1111/gcb.14820>, 2020.

Zachle, S. and Friend, A. D.: Carbon and nitrogen cycle dynamics in the O-CN land surface model: 1. Model description, site-scale evaluation, and sensitivity to parameter estimates, *Glob. Biogeochem. Cycles*, 24, <https://doi.org/10.1029/2009GB003521>, 2010.