Response to reviewers

Response in blue

Summary

The authors address a gap within literature that explores how terrestrial vegetation can modulate water scarcity in future climate and CO_2 concentrations. To isolate stomatal and leaf area responses to climate change and rising CO_2, they analyzed a set of model simulations from JULES with prescribed atmospheric forcings and CO_2. They find that stomata response can alleviate global water scarcity, particularly in the tropics and already wet regions, but can amplify water scarcity in water-limited arid and semi-arid regions. I believe this study is a valuable contribution to the scientific literature and appreciate the authors' analysis and thorough discussion of the study's limitations. Additionally, the use of Water Scarcity Index is especially compelling as it incorporates water demands and has direct implications for future water availability.

Thank you for the summary. We greatly appreciate your time and effort in reviewing the paper.

General comments

The authors focus on a single land-surface model with prescribed atmosphere. The authors could briefly discuss how the findings of these manuscript fit into the broader context. How can the findings from this single model study be applied to other models?

Thank you for your suggestion. We would not expect the findings of this study to be applied to other land surface models but agree it would be useful to discuss how we might expect other land surface models to compare to JULES. We will add the following to the Discussion section:

"Since only one land surface model was assessed in this study, further work could test additional models to examine the sensitivity of the results. We would anticipate broadly consistent outcomes across land surface models in the STOM simulations, as many employ stomatal conductance parameterisation schemes derived from similar formulations. However, we would expect a wider spread of responses in the VEG simulations, given that different Dynamic Global Vegetation Models apply alternative approaches to dynamic vegetation compared with the TRIFFID scheme used in JULES (Sitch et al., 2008)."

The findings from this study could be used to encourage the hydrology modelling community to prioritise incorporating the plant physiological response into hydrology models. The following has been added to the Conclusion section:

"Our findings highlight the need to incorporate vegetation dynamics, primarily physiological forcing, into hydrology models to improve the robustness of water scarcity assessments."

The stomatal conductance model used in JULES is the Leuning one, and it would benefit readers to include a brief explanation on the variables represented in the Leuning model and how it differs from other models (e.g., Ball-Berry, Medlyn, etc.) in formulation and impact on water scarcity.

Thank you for the suggestion. A more thorough explanation of the stomatal conductance model will be added to the Appendix:

"JULES uses a coupled canopy conductance and photosynthesis model (Cox et al., 1998) where stomatal conductance to water vapour g_s (m s^{-1}) is based on:

$$g_s = -1.6A\frac{RT^*}{c_i - c_a} \quad (1)$$

where A is the net photosynthetic rate (mol CO_2 m^{-2} s^{-1}), R is the universal gas constant (J K^{-1} mol^{-1}), T is the leaf surface temperature (K), c_i the internal CO_2 partial pressure (Pa), c_c the leaf surface CO_2 partial pressure (Pa) and factor of 1.6 accounting for molecular diffusivity differences between water and CO_2. Vapour deficit at the leaf surface (D, kg kg^{-1}) affects stomatal conductance through the gradient between c_a and c_i is based on the equation by Jacobs (1994):*

$$\frac{c_i - \Gamma^*}{c_a - \Gamma^*} = f_0\left(1 - \frac{D}{D_{crit}}\right) \quad (2)$$

where Γ^* is the photorespiration compensation point (Pa) and D_{crit} and f_0 are PFT-specific calibration parameters, which are directly related to the parameters from the Leuning (1995) model (for details see Cox et al., 1998). Potential non-stressed leaf level photosynthesis is calculated in JULES using the C3 and C4 photosynthesis models of Collatz et al. (1991) and Collatz et al. (1992) respectively.

The Jacobs formulation is a simplified version of the Leuning (1995) model, which in turn is based on the (Ball et al., 1987) model but depends on humidity deficit at the leaf surface instead of relative humidity."

We note that the (Medlyn et al., 2011) stomatal model also incorporates a humidity deficit term and a minimum conductance term that is only used when the latter is known. This and the three other formulations mentioned above are structurally similar and can be fitted to obtain similar responses with common parameters. The main differences are in the dependence to humidity deficit in Leuning (1995), Jacobs (1994) and Medlyn et al (2011), but dependence to relative humidity in Ball et al (1987).

Given these similarities, we would expect the impacts of the different formulations on projected changes in water scarcity to be minimal in comparison with the effect of including or excluding the responses to changing atmospheric CO2 concentrations.

Stomatal conductance and leaf area contributions to water metrics may have nonlinearities. Stomatal conductance is linked to photosynthesis, which then affects leaf area. The authors can consider addressing some of these nonlinearities and how they might influence results.

We agree that stomatal conductance and leaf area contributions to water metrics may have nonlinearities, which will emerge naturally in our simulations. The effect of CO_2 on LAI can be isolated by comparing S4–S2 (CO2: STOM+VEG) with S3–S1 (CO2: STOM). When CO_2-driven LAI changes are included in CO2: STOM+VEG, global median water supply is reduced by ~10–15% (Fig. 5d) and water scarcity is subsequently increased by ~5–10% (Fig. 5e), relative to CO2: STOM. However, examining these in further detail would increase the length of an already long and detailed paper, so we propose to leave investigation of that issue for future work.

The use of physiological and structural response in addition to stomatal and leaf area responses in the introduction is confusing to the reader. It could be helpful to directly link physiological and structural responses to stomatal and leaf area responses. I understand that the authors define "physiological forcing" in the terminology, but the manuscript would benefit if the distinction is made more clear earlier. Additionally, does "vegetation distribution change" refer the structural response?

Thank you for bringing this to our attention. We will include the following at the beginning of the introduction for clarification, and also all "vegetation *distribution* changes" have been changed to "vegetation *structural* changes" to make this less confusing.

Terminology clarification: Throughout this manuscript, we use the following terms consistently:

- **Stomatal response** – changes in stomatal conductance (i.e., stomatal opening and closure).
- **Structural response** – changes in vegetation structure (leaf area and canopy coverage).
- **Physiological response (or forcing)** – CO_2-induced changes encompassing both stomatal behaviour and vegetation structure (leaf area and canopy coverage).

Minor specific comments

Table 1a and b were very helpful in understanding the different simulations. An additional line separating calculations vs simulations would help the reader interpret the table, though I do appreciate the bolding attempts for that.

Thanks for the suggestion. A line has been added to separate the simulations and calculations in Table 1.

Figure 1 could benefit from removal of the legend since data from only one simulation was used to create the plots. Instead, an overall title (e.g., 'Annual mean timeseries from S1. CLIM: STOM). The removal of the legend will also allow the plots to be larger.

Legends have been removed from Figure 1.

Runoff as a proxy for water supply intuitively makes sense, but has not been explicitly related in the introduction or methodology section. A sentence for why runoff is used as a proxy in the methodology section would be helpful to the reader. Additionally, surface and sub-surface runoff are analysed, and a distinction and description for the two and what they can tell us would be helpful.

Thank you for the suggestion. The following will be added to the Methods section:

"Runoff is used as a proxy for water supply because it represents the fraction of precipitation that is not lost to evapotranspiration and is therefore available for water resources. Total runoff is taken from the output of the simulations and includes both surface (overland flow generated when precipitation exceeds infiltration capacity or soil saturation) and sub-surface runoff (lateral drainage through the soil column) at the grid box scale."

L360: The "decreases" in the last two sentences are not specified and confusing to the reader.

Thank you for pointing this out. We have amended the text which hopefully makes it clearer:

"When CO_2-induced vegetation structural changes are also included in the CO2: STOM+VEG simulations (Fig. 6h,i), total supply still increases overall, as the supply reductions associated with CO_2-driven structural vegetation expansion are relatively small and less apparent in the plots. However, these modest reductions translate into substantial increases in WSI in arid regions such as the Middle East and northern and southern Africa (Fig. 6i), where baseline water supply is already low."

The right plot in Fig. 8 "% difference" could state "% difference of median WSI" for the reader's ease of reading.

Thanks, this will be amended.

Technical corrections

L151: extra space after period: "bias correction ."

L231: Extra space between "SSP2" and "from"

L264: extra ";" after "Fig. 2n"

L416: Extra ",)" after "(Fig. 9d)"

Generally, double check for extra spaces, missing spaces, commas, and semicolons throughout the manuscript.

Thank you for highlighting these corrections and formatting issue. The corrections will be made and manuscript carefully checked.