Impact of the representation of stomatal conductance on model projections of heatwave intensity

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Stomatal conductance links plant water use and carbon uptake, and is a critical process for the land surface component of climate models. However, stomatal conductance schemes commonly assume that all vegetation with the same photosynthetic pathway use identical plant water use strategies whereas observations indicate otherwise. Here, we implement a new stomatal scheme derived from optimal stomatal theory and constrained by a recent global synthesis of stomatal conductance measurements from 314 species, across 56 field sites. Using this new stomatal scheme, within a global climate model, substantially increases the intensity of future heatwaves across Northern Eurasia. This indicates that our climate model has previously been under-predicting heatwave intensity. Our results have widespread implications for other climate models, many of which do not account for differences in stomatal water-use across different plant functional types, and hence, are also likely under projecting heatwave intensity in the future.

Heatwaves are extreme phenomena that have major impacts on environmental, social, health and economic systems1. We define heatwaves as a series of three or more consecutive days during which daily maximum temperatures are higher than the calendar-day 90th percentile2. The frequency, intensity and duration of heatwaves are increasing in many parts of the globe3–5. Observations have highlighted an increase in the length of European heatwaves6 and the frequency of heatwave occurrence in China7 and Australia2,8. For example, the 2003 summer heatwave affected much of Western Europe and likely provided a precursor to future extremes across this region9. Many of these observed large-scale heatwaves have been linked to human activity via global warming10,11.

Future warming linked with increases in greenhouse gases is expected to increase the frequency, intensity and duration of heatwaves further3–12, particularly across the mid-latitudes including North America and Europe13,14. Heatwaves are associated with large-scale synoptic states15,16, which are influenced by modes of climate variability17. However, it is now well established from observational18 and modelling studies19,20 that heatwaves are also strongly modulated by the land surface if the synoptic scale weather generates persistent anticyclonic patterns and the planetary boundary-layer strongly couples the land to the atmosphere over consecutive days21. Under these circumstances, heatwaves intensify as desiccated soils and a surface radiation balance dominated by the exchange of sensible heat is coupled with the boundary-layer to lead to events such as the “mega-heatwaves” experienced in Europe during 2003 and 201019,21. Although the detailed role of the land surface on the exchange of water and energy during heatwaves remains uncertain22, there is evidence that capturing the detailed connection between the land and the atmosphere, and how soil moisture impacts the surface energy balance to moderate or intensify heat waves, is necessary to produce realistic simulations of these phenomena22.

Within climate models, land surface models (LSMs) simulate soil moisture and partition available radiation at the surface between sensible and latent heat fluxes23. For vegetated surfaces, in particular over forests, the latent heat flux is principally controlled by stomata, as plants exchange water for carbon. Our ability to accurately simulate how soil moisture states and soil moisture variability affects heatwaves, therefore relies at least in part, on

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accurately modelling stomatal conductance ($g_s$) under current and future CO$_2$ concentrations. At the leaf scale, experiments commonly find that increasing CO$_2$ results in increased photosynthesis$^{24,25}$ and reduced water loss via lower $g_s$ 26–28. However, there is increasing evidence$^{29,30}$ that we cannot easily transfer our leaf/canopy level understanding of the response of transpiration due to CO$_2$ to ecosystem scales. Nevertheless, any CO$_2$-induced change in transpiration and/or soil “water-savings”, has the potential to alter future soil moisture state, soil moisture variability, and transpiration, which may then feedback on the development of heatwaves over several days$^{31}$. Given that heatwaves are associated with synoptic state and persistent anticyclonic conditions or so-called “blocking/persistent highs”$^{32,33}$, these feedbacks are more likely to affect heatwave intensity than duration or frequency.

To date, the representation of $g_s$ in LSMs has been largely based on empirical models$^{33–35}$. These models typically assume that differences in plant water use strategy are only tied to the photosynthetic pathway (C3 vs. C4). This assumption is not supported by experimental evidence; instead leaf level measurements suggest that plant water use strategies vary among species (or plant functional types, PFTs)$^{36}$. Ignoring these differences among PFTs will likely result in errors in the simulated flux of moisture to the atmosphere. A recent collation of a global database of leaf-level $g_s$ measurements$^{37}$ from 319 species across 56 field studies was used to parameterise differences in plant water use strategy among PFTs within the Community Atmosphere Biosphere Land Exchange (CABLE) model$^{32}$. Parameters were estimated for each of the models PFTs by fitting Eq. 1 (see Methods) to this leaf-level dataset using a non-linear mixed effects model$^{39}$.

This new $g_s$ model$^{37,38}$ is similar in functional form to the previous empirical model$^{32}$ used in CABLE and many other LSMs but is derived following optimal stomatal theory. Consequently, model parameters carry biological meaning and can be hypothesised to vary with climate and plant water use strategy$^{37}$. Such variations are supported by experimental data$^{39}$. Offline CABLE simulations$^{39}$ and coupled land-atmosphere simulations$^{29}$ performed using the Australian Community Climate System Simulator (ACCESS1.3b$^{40}$) showed that this parameterisation led to a reduction in transpiration (up to 1 mm day$^{-1}$) across boreal regions, which resulted in an increase in daily minimum and maximum temperatures (by up to 1 °C). These changes in contemporary simulations of water fluxes and daily warm temperature extremes were an improvement in the model's climatology in comparison to observations during the boreal summer, especially over Eurasia$^{39}$.

We extend our previous work$^{38,39}$ to examine how an alterantive $g_s$ model, constrained by a global synthesis of leaf-level measurements, impacts upon future simulations of the likely incidence of heatwaves. We use the “business as usual” emission scenario (Representative Concentration Pathway 8.5 (RCP8.5))$^{41}$ with the ACCESSv1.3 climate model. To the best of our knowledge, this is the first paper to implement a $g_s$ model within a global climate model focussing on future climate simulations, where the $g_s$ model parameters vary per PFT and are derived from best available data. We focus specifically on Eurasia for several reasons. Firstly, this is the region where the new $g_s$ scheme improved ACCESS's climatology of evaporation and warm extremes$^{39}$. Secondly, a previous evaluation of ACCESS's simulations of extremes has shown large biases in extreme temperatures linked to clouds over North America$^{42}$ and hence we avoid analysing this continent. Thirdly, Eurasia was shown to be sensitive to the parameterization of $g_s$ in earlier ACCESS experiments$^{39}$ and finally, work by many researchers$^{19,21,43}$ hints at this region being susceptible to large changes in warm extremes and heatwaves in the future.

Results

We first examine changes in warm extremes and surface moisture fluxes as illustrated in Fig. 1 showing the difference in mean Boreal summer (June-July-August) daily maximum temperature ($T_{max}$, Fig. 1a), warmest yearly maximum temperature ($T_{Xx}$, Fig. 1b), and evapotranspiration (ET, Fig. 1c), averaged over 20 year intervals (2020–2099), between the new and the default $g_s$ scheme (i.e., Experiment minus Control). $T_{max}$ increases commonly by ~1 °C but by more than 1.5 °C over Western Europe and 2 °C in some regions. The impact of the new $g_s$ scheme on $T_{Xx}$ is larger, reaching 5 °C over widespread regions. Not surprisingly, there is a strong similarity between the patterns of temperature increases, decreases in ET (Fig. 1c), and subsequent decrease in precipitation (Fig. 1d), consistent with our previous work$^{39}$. We note that the difference in both $T_{max}$ and $T_{Xx}$ between models is largest during the period 2040–2059 and decreases towards the end of the century. One possible explanation for this decrease is that at high leaf temperatures (ca. 30 °C), photosynthesis and stomatal conductance (and thus transpiration) are reduced due to photosynthetic inhibition (Fig. S2). This response to high temperature mimises the differences in transpiration between the models that originally resulted from the more conservative water use parametrisation in the new scheme.

Furthermore, the two $g_s$ schemes have different sensitivities to vapor pressure deficit (VPD), with the default model showing stronger sensitivity at high VPD (> 3 kPa)$^{34}$. Thus, as dryland expansion accelerates under climate change$^{34}$, and the air temperature and VPD increase towards the end of the 21st century, the difference in predicted transpiration between the two models becomes smaller (Fig. S2 and related text), which potentially accounts for the smaller effect on $T_{max}$ and $T_{Xx}$ compared to earlier in the century. Nevertheless, there are still large differences between the models across most of Eurasia at the end of the century (2 to 4 °C for $T_{Xx}$s).

The increases in $T_{max}$ and $T_{Xx}$ and a decrease in ET can be clearly seen in the probability density functions (PDFs, Fig. 2). There is a clear shift to the right for the PDF of $T_{max}$ and $T_{Xx}$, but the limits of the lower and upper tails are mostly unchanged. The new $g_s$ scheme does not lead to the emergence of temperatures not previously experienced across the region; rather, it leads to a much more frequent occurrence of hot temperatures. Clearly, this change is linked to a shift in the PDF of ET to the left, such that ET exceeding 4 mm day$^{-1}$ is rare with the new $g_s$ scheme, but common using the old scheme.

We next examined the influence of the change in $g_s$ on heatwave duration, frequency and intensity (see Methods for definition). The changes in heatwave duration and frequency were very small, but changes in heatwave intensity (HWI) were large (Fig. 3). During the earlier part of the century (2020–2039), there are regions of both increases and reductions in HWI indicating that the forcing associated with the change in $g_s$ is commonly smaller than internal model variability. However, by 2040–2059, the new scheme results in an increase in HWI
everywhere, with particularly large increases over western Europe, western Russia and eastern China, where HWI increases by 6–7 °C. Similarly to the changes in T\textsubscript{MAX} and TX\textsubscript{x}, the magnitude of the increase in HWI decreases towards the end of the century, but remains higher than 5 °C in many regions.
increasing LAI55 and declining) by 2081–2100 46. It is also similar in magnitude to the estimate reported for the change in...

our results do show that gs strongly affects the intensity of heatwaves over Eurasia and is therefore further evi-

tence that land-atmosphere interactions are an important driver of extreme temperature events.

These increases are additive to those likely caused by increasing greenhouse gases over the same period 47. The...

ACCESS, but clearly this may vary in other climate models. As both simulations prescribed the same LAI, the...

parameterisation of gs had no impact on the frequency or duration of heatwaves, since these are primarily driven by...

Discussion and Conclusion

The increase in future (2020–2099) simulated TXx resulting from changing the representation of gs is approxi-
mately 4–5 °C over Western Europe. This sensitivity to gs can be put into context by recognising that this change is...

improved parameterization of gs led to increases in temperature and improved simulations39, particularly between

around 45–60°N. The increases predominately occurred across regions defined as evergreen needleleaf forest, Tundra, and crop PFTs.

The stomatal parameterisation we used in ACCESS accounts for differences in stomatal behaviour between

PFTs and is supported by a global synthesis of leaf-level stomatal data36, in line with both predictions from optimi-

mal stomatal theory27,48 and the leaf and wood economic spectrum49,50. This empirical basis lends support to the...

we have assumed all vegetation to have the same drought sensi-
tivity. Observations suggest that vegetation adapted to different hydroclimates have different sensitivity51, which

have significant implications for socio-economic and environmental systems. We note that our revised param-

eterisation of gs had no impact on the frequency or duration of heatwaves, since these are primarily driven by...

larger-scale synoptic-scale processes such as blocking highs 57 and changing patterns of circulation58. However,

our results do show that gs strongly affects the intensity of heatwaves over Eurasia and is therefore further evi-
dence that land-atmosphere interactions are an important driver of extreme temperature events.
Methods

New representation of stomatal conductance. The default gs model used in ACCESSv1.3b40 has been described in detail in the literature. The new gs scheme follows the form:

\[ g_s' = g_0 + 1.6 \left( 1 + \frac{g_s^2}{\sqrt{D}} \right) \frac{A}{C_a} \]

where \( A \) is the net assimilation rate (\( \mu \text{mol m}^{-2} \text{s}^{-1} \)), \( C_a (\mu \text{mol mol}^{-1}) \) and \( D \) (kPa) are the CO\(_2\) concentration and the vapour pressure deficit at the leaf surface, respectively, and \( g_0 (\mu \text{mol m}^{-2} \text{s}^{-1}) \) and \( g_1 \) (kPa\(^{-0.5}\)) are fitted constants representing the residual stomatal conductance as A rate reaches zero, and the slope of the sensitivity of gs to A, respectively. \( g_0 \) is zero, leaving one key model parameter, \( g_1 \), which theoretically represents the marginal carbon cost of water.

The model was parameterised for the different PFTs (Fig. S1) using a global synthesis of stomatal measurements compiled from 314 species, across 56 field sites, covering the Arctic tundra, boreal regions, temperate forests and tropical rainforest biomes. Values are shown in Table S1. The default gs scheme in CABLE has two fitted parameters which only vary by photosynthetic pathway (C3 versus C4) but not by PFT. More details on the differences between the default and new scheme and the implementation of the new scheme in CABLE can be found in our earlier work.

Simulations. The ACCESS model setup is identical to our previous work in evaluating the new gs model under current climate, except that simulations use sea surface temperatures from a previous fully-coupled simulation with ACCESS1.3 driven by the RCP8.5 emission scenario (official CMIP5 submission). Five ensembles were run; each initialised a year apart, with the default gs scheme (i.e., the control), and the new scheme (i.e., the experiment). All results shown are for the ensemble mean. We performed statistical significance testing of the differences between the experiment and the control using the student's t-test at 95% confidence interval, and tested for field significance using the false discovery rate method. Similar to our previous work, nutrient-limited carbon pool dynamics and dynamic phenology were not activated, as the focus was on biophysical effects of the new gs scheme. Leaf area index (LAI) was prescribed as a monthly climatology derived from MODIS estimates. Results are also only shown between 30°W-150°E longitude and 30°N-80°N latitude, corresponding to the region where the new gs scheme improved ACCESS's climatology of ET and warm extremes when compared to observations.

Heatwave definition. Following the literature on heatwaves (HWs), we use thresholds based on percentiles rather than absolute values, with an event defined as temperatures exceeding the 90th percentile of daily maximum temperatures for at least 3 consecutive days. The percentiles are computed for each calendar day over tiles rather than absolute values, with an event defined as temperatures exceeding the 90% percentile of daily events during summer; the HW-frequency is the number of HW events; the HW-intensity is the mean temperature of the HW events; and the HW-max-intensity is the maximum temperature during the HW events.

Indices are averaged across the 5 ensembles for the control and experiment and the ensemble mean difference is shown between the experiment and the control.

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Author Contributions
A.J.P. conceptualized the project. J.K. carried out all the analysis. M.D.K. and J.K. implemented the new stomatal conductance scheme in CABLE. J.K. and R.L. ran all ACCESS simulations. B.E.M. and Y.-P.W. developed the new and default stomatal conductance schemes respectively. S.E.P.-K. assisted in implementing the heatwave indices. J.K., M.D.K. and A.J.P. lead the writing and all other co-authors made substantial contributions towards several draft manuscripts.

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