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Simulated changes in aridity from the last glacial maximum to $4xCO_2$

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Abstract

Aridity is generally defined as the 'degree to which a climate lacks moisture to sustain life in terrestrial ecosystems'. Several recent studies using the 'aridity index' (the ratio of potential evaporation to precipitation), have concluded that *aridity* will increase with CO_2 because of increasing temperature. However, the 'aridity index' is—counterintuitively—not a direct measure of *aridity* per se (when defined as above) and there is widespread evidence that contradicts the 'warmer is more arid' interpretation. We provide here an assessment of multi-model changes in a broad set of *aridity* metrics over a large range of atmospheric CO_2 concentrations ranging from conditions at the last glacial maximum to $4xCO_2$, using an ensemble of simulations from state-of-the-art Earth system models. Most measures of *aridity* do not show increasing *aridity* on global scales under conditions of increasing atmospheric CO_2 concentrations and related global warming, although we note some varying responses depending on the considered variables. The response is, furthermore, more nuanced at regional scales, but in the majority of regions *aridity* does not increase with CO_2 in the majority of metrics. Our results emphasize that it is not the climate models that project overwhelming increases of *aridity* with increasing CO_2, but rather a secondary, offline, impact model—the 'aridity index'—that uses climate model output as input.

1. Introduction

The common term to describe the hydroclimatological state of the land surface is *aridity*. Given a summary of textbook definitions, high *aridity* is usually defined as a lack of available moisture to sustain and promote life in terrestrial ecosystems (see supplementary information available at stacks.iop.org/ERL/12/114021/mmedia). At climatological time scales, a lack of moisture is mainly determined by (i) terrestrial water fluxes such as precipitation *P*, evapotranspiration *E* and runoff *Q*, and (ii) processes being partly controlled by or controlling these fluxes such as e.g. photosynthetic rate of plants or soil moisture (SM). These fluxes and mechanisms consequently define the *aridity* of the land surface. In the recent literature, it is commonly stated that GCMs (global climate models) project increases in global *aridity* over the 21st century (Feng and Fu 2013, Sherwood and Fu 2014, Huang *et al* 2016, Scheff and Frierson 2015). Several studies further suggest that increasing *aridity* is a direct thermodynamic consequence of global warming under conditions of increasing atmospheric CO_2 concentrations (Fu and Feng 2014, Sherwood and Fu 2014).

However, there is strong observational evidence pointing towards decreasing *aridity* under conditions of increased atmospheric CO_2 and the associated warming, thus constituting a 'global aridity paradox' (Roderick *et al* 2015). Ice core data show elevated levels of atmospheric dust concentrations occurring in cold, glacial time periods (Lambert *et al* 2008), often interpreted as pointing towards more arid conditions

(Muhs 2013). There is further evidence derived from tree ring data showing that water use efficiency (the ratio of photosynthetic rate to transpiration) in European forests increased over the last 100 years because of increasing CO_2 (Frank *et al* 2015). Using remote sensing techniques, greening trends were widely observed since the early 1980s and especially in semi-arid regions (Donohue *et al* 2009, de Jong *et al* 2011), being, in part, a possible response to elevated levels of CO_2 (Donohue *et al* 2013, Zhu *et al* 2016, Obermeier *et al* 2017). Additionally, the generalized conclusion of more arid conditions in a warmer world is challenged by large uncertainties underlying observed and projected *aridity* changes (Sheffield *et al* 2012, Greve *et al* 2014, Greve and Seneviratne 2015).

A metric used in some recent studies (Feng and Fu 2013, Sherwood and Fu 2014, Huang *et al* 2016, Scheff and Frierson 2015) to identify changes in the hydroclimatological conditions at the land surface is the *aridity index*, which is defined as the ratio of potential evaporation to precipitation E_p/P (with higher values indicating higher *aridity*). The *aridity index* provides a simple model representing the complex interplay of atmospheric water demand and atmospheric water supply, and is commonly understood as a general quantity to characterise the hydroclimatological state of the land surface. The *aridity index* is, however, not directly related to the common definition of *aridity* as mentioned above and is only a measure of atmospheric demand for evapotranspiration vs moisture supply through precipitation. In current formulations, the *aridity index* is projected to increase over the 21st century (Feng and Fu 2013, Sherwood and Fu 2014, Fu and Feng 2014, Scheff and Frierson 2015), mostly due to larger increases in E_p relative to P. E_p is commonly parametrized by using reference evaporation based on a modified Penman-Monteith equation (E_{ref}, Allen *et al* 1998), which is also recommended by the Food and Agriculture Organization (FAO). However, many other formulations for E_p have been shown to yield weaker increases in projected *aridity index* compared to E_{ref} (Milly and Dunne 2016). The increase in E_{ref} does occur partly due to an increase in vapor pressure deficit (VPD). Increases in VPD on land are due on the one hand toincreasing temperatures and the nonlinear increase of saturation vapor pressure as a function of temperature (Clausius-Clayperon relationship) (Sherwood and Fu 2014), as well as reduced inputs from the surface to atmosphere (i.e. decreasing E) due to lack of soil moisture or increasing plant water use efficiency (Berg *et al* 2016).

2. Why should we revisit our current understanding of changes in aridity?

It is very important to note, that despite the frequent use of the *aridity index* in recent studies, assessing changes in *aridity* as a measure of water availability does not require the use of a secondary, offline, impact model. Indeed, the relevant fluxes and quantities to comprehensively assess *aridity* already count among the standard output of state-of-the-art climate models. Over the global land surface, terrestrial water fluxes (P, E and Q) are on average projected to increase within the 21st century (Roderick *et al* 2015), although regional assessments and changes in other measures of *aridity* (e.g. relative humidity and SM) are more uncertain and include decreases in some regions (Orlowsky and Seneviratne 2013, Greve and Seneviratne 2015). In an idealised equilibrium experiment using a modified version of the NASA Goddard Institute for Space Studies (GISS) climate model (Russell *et al* 2013), a recent study further found that over a very large range of atmospheric CO_2 concentrations (80 to 80 000 ppm), global land P and Q consistently increase with atmospheric CO_2. However, it is not clear if these results also apply to other climate model simulations.

Taking these considerations into account, we assess here changes in a variety of terrestrial water fluxes and quantities that provide a comprehensive selection of direct measures of *aridity*, comprising P and Q, gross primary productivity (GPP), total soil moisture (SM), near-surface relative humidity (rH) and also water use efficiency (WUE = GPP/E_t, with E_t being transpiration). These measures are, when put in the appropriate context, of immediate relevance to ecosystems and societies. Decreasing P is of interest in the context of *meteorological aridity*, less Q is of interest in the context of *hydrological aridity*, depletion of soil moisture is of interest in the context of *agricultural aridity* (Seneviratne *et al* 2012), decreasing rH is of interest in the context of *atmospheric aridity*, and decreases in GPP and WUE are of interest in the context of *agro-ecological aridity* (Roderick *et al* 2015). Considering individual metrics could therefore potentially provide useful information for specific impact assessments, but a complete understanding of anticipated changes in *aridity* requires a joint consideration and interpretation of all metrics. In this context it is further important to note that these metrics are not independent of each other and that relations between individual metrics potentially differ regionally.

3. Climate model data and methodological approach

The common assumption that a warmer world implies decreasing water availability is addressed by investigating changes in the relevant quantities (P, Q, GPP, SM, rH, WUE) using state-of-the-art Earth system models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble. In order to draw comprehensive conclusions, both equilibrium and transient experiments are analysed to cover a wide range of possible CO_2 concentration levels. By doing so we are able to systematically review global and regional *aridity* changes with respect to increasing atmospheric CO_2 concentrations and associated global warming.

Equilibrium experiments provide a greenhouse gas forcing held constant over a long time period, but not all CMIP5 models undertook the relevant experiments. We use here a subset of seven models providing data for three different equilibrium experiments conducted within CMIP5. These are: (i) Last Glacial Maximum (LGM, CO_2 concentration held constant at 185 ppm), (ii) pre-industrial Control (piC, 280 ppm) and (iii) abrupt 4 times CO_2 (4xCO_2, 1120 ppm). Please note that within LGM experiments large areas are glaciated and mean sea level is lower, e.g. leading to altered atmospheric circulation patterns and thereby constituting changes not just due to prevailing CO_2 concentrations. We further use transient historical simulations and projections following the RCP8.5 concentration pathway with CO_2 concentrations ranging from 280 ppm to ca. 900 ppm.

All data are regridded to a common 2.5° × 2.5° grid and climatological (50 year) annual averages for the equilibrium runs and averages from each year of the transient runs are computed. To compute global land averages (area-weighted) we only use those grid points which are common in all variables (T, P, Q, GPP, E_t, WUE, SM, rH). By doing so we automatically exclude ocean grid points, since E_t (used to compute WUE), Q, GPP, WUE and SM are only defined for the land portion of each model. To further avoid false estimates of P and E at coastal grid points we also exclude all grid points where the 50 years mass balance P–E–Q is significantly different from zero. This accounts for the fact that both P and E are averaged over both the land and ocean portion of coastal gridboxes, whereas Q is defined for the land portion only. For all variables in the LGM experiments we further exclude areas covered by glaciers (which were set to missing values in IPSL-CM5A-LR). We further exclude unrealistically small E_t estimates of IPSL-CM5A-LR in the LGM experiment. Values of SM in the transient runs from MRI-CGCM3 are ignored due to unrealistic time series in some tropical regions. We also note that the results for piC and 4xCO_2 (for which more than the selected seven models are available) are not sensitive to our model selection (not shown).

In addition to the direct model output we compute estimates of the *aridity index* (E_p/P) based on $E_p = E_{ref}$ (Allen *et al* 1998) to enable a direct comparison to previous results (Feng and Fu 2013, Sherwood and Fu 2014, Fu and Feng 2014, Scheff and Frierson 2015). This approach requires, besides T and rH as mentioned before, also estimates of latent and sensible heat fluxes and surface wind speed (see supplementary information).

For an overview of all models and metrics (and which metrics are covered by which models) please refer to table 1.

Table 1. Overview of CMIP5 climate models. We use here only those models that provide data for the LGM, piC and 4xCO_2 equilibrium experiments and annual data for the historical simulations and RCP8.5 projections. Crosses denote which metrics are covered by each model. *Aridity index* is computed using P, temperature, rH, wind speed and the heat fluxes. Please note that there are no transient model experiments from MPI-ESM-P.

Model	P, Q, E_t	SM	rH	GPP, WUE	Aridity index
CCSM4	x		x	x	
CNRM-CM5	x	x	x		x
FGOALS-g2	no Q	x			
IPSL-CM5A-LR	x	x		x (no WUE for LGM)	
MIROC-ESM	x	x	x	x	x
MPI-ESM-P	x	x		x	
MRI-CGCM3	x	x	x		x

4. Changes in aridity

4.1. Global mean changes

We first assess changes in the relevant variables at global scales. Figure 1 displays climatological (LGM, piC and 4xCO_2) and mean annual (transient runs) values of T, P, Q, rH, GPP, E_t and WUE of every model averaged over global land and plotted as a function of CO_2. It is clearly evident that at global scale P, Q, GPP and WUE generally increase with increasing CO_2 in both the equilibrium experiments and the transient runs (although absolute changes are different between models). Changes are usually larger between LGM to piC than between piC and 4xCO_2. For the terrestrial hydrologic fluxes (P and Q) within the transient runs the relationship appears to be near-linear with CO_2. The increase in GPP and WUE clearly saturates at very high levels of CO_2 for IPSL-CM5A-LR, whereas it keeps increasing for other models. Little change in E_t combined with large relative changes in GPP lead to a steady increase in WUE with CO_2. Changes in rH are mixed and model-dependent; an increasing tendency for MRI-CGCM3 accompanied by nearly constant values for CNRM-CM5 and a general decreasing tendency for the other models.

4.2. Regional changes

Although the global assessment shows a general decrease in *aridity* under increased CO_2 conditions, there are important regional variations. In order to assess local changes we compute climatological averages from the LGM, piC and 4xCO_2 model experiments at grid point scale.

4.2.1. Hydroclimatological changes

Figure 2 displays maps of ensemble-mean changes in P, Q and rH between (i) LGM and piC (figures 2(*a*)–(*c*) and (ii) piC and 4xCO_2 (figures 2(*d*)–(*f*)). Most notably there is a general increase in P and Q in the northern high latitudes. There is further a general increase in tropical Africa and South East Asia, whereas tropical South America shows a strong increase between LGM and piC, but non-robust changes or even decreases

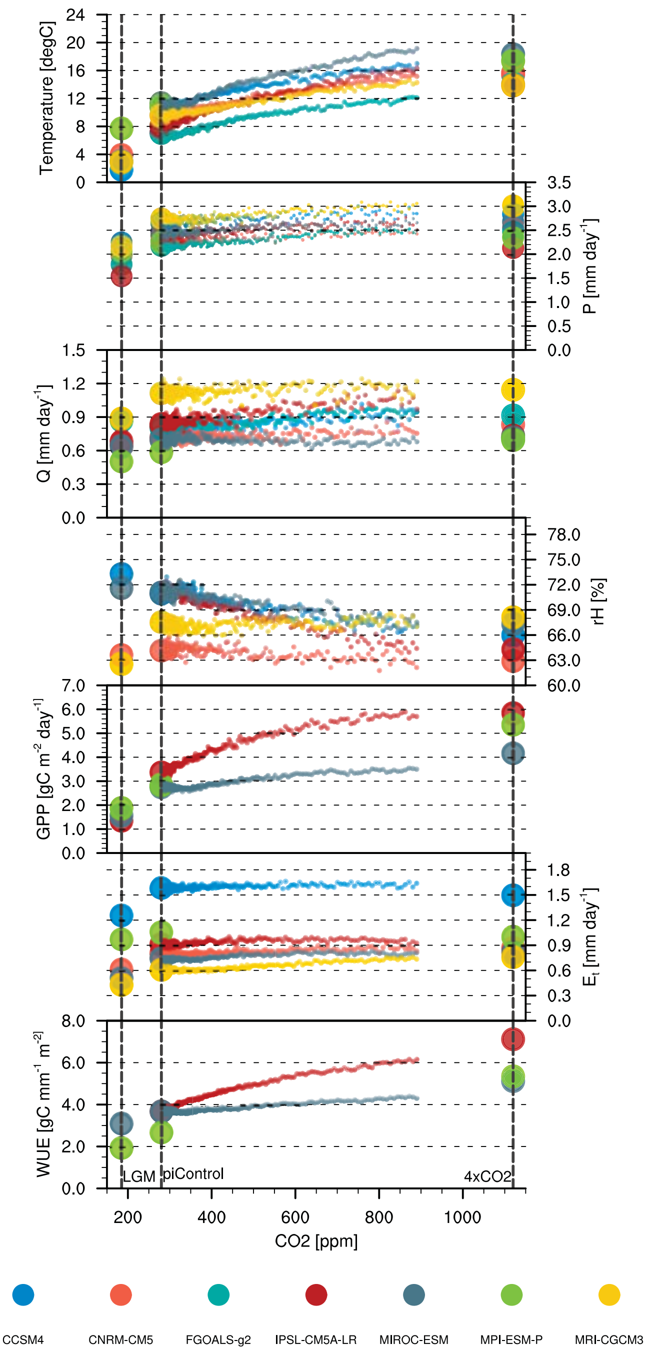

Figure 1. Assessing global changes in hydroclimatological variables within the 60° *S*–60° *N* domain. (1st panel) Global land temperature, (2nd panel) *P*, (3rd panel) *Q*, (4th panel) rH, (5th panel) GPP, (6th panel) E_t and (7th panel) WUE = (GPP/E_t) for the global terrestrial surface as a function of atmospheric CO_2 concentration (LGM: 185 ppm, piC: 280 ppm, 4xCO_2: 1120 ppm). Small symbols correspond to mean annual values from the historical and RCP8.5 runs (ranging from 280 ppm in 1850 to ca. 900 ppm by the end of the 21st century).

between piC and 4xCO_2. In parts of southwestern North America and southern Africa there is a decrease in both *P* and *Q* from LGM to piC to 4xCO_2. The Mediterranean region shows almost no changes occurring between LGM and piC, followed by decreasing *P* and *Q* between piC and 4xCO_2.

The response in rH shows, in most regions, a general increase between LGM and piC, which is contrasted by a general decrease in rH between piC and 4xCO_2. There are, nonetheless, a few notable exceptions, either showing increases from LGM to piC and further to 4xCO_2, e.g. in several monsoon-dominated regions such as eastern Africa and southern Asia, or continuous decreases, e.g. in the western US, the Amazon region and southern Africa. However, we note again that the results for rH are model-dependent in many regions.

4.2.2. *Agro-ecological changes*

Ensemble-mean changes in agro-ecological variables are displayed in figure 3 and most notably show an

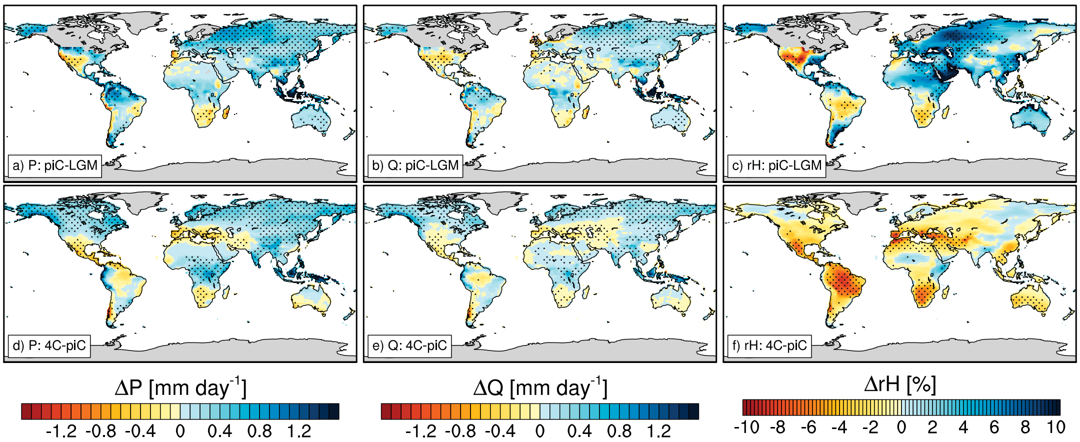

Figure 2. Assessing regional changes in hydrological variables. (1st column) Changes in *P*, (2nd column) *Q* and (3rd column) rH for mean climatic conditions between LGM and piC (top row) and piC and 4xCO_2 (bottom row). Stippling denotes regions in which six out of seven (for *P*), five out of six (for *Q*) and four out of four (for rH) models agree in sign.

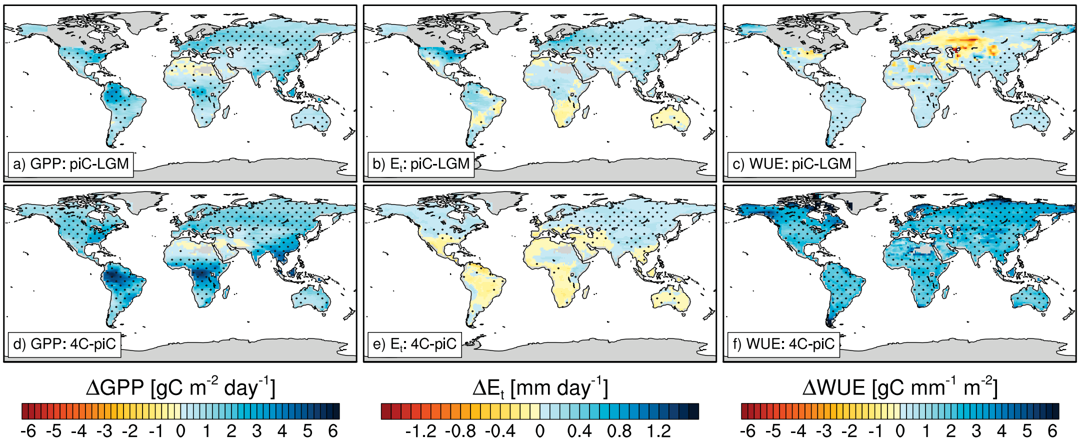

Figure 3. Assessing regional changes in ecological variables. Changes in GPP (left column), E_t (middle column) and WUE (right column) for mean climatic conditions between LGM and piC (top row) and piC and 4xCO_2 (bottom row). Stippling denotes regions in which three out of three (for WUE at piC-LGM) or four out of four (for WUE at 4 C-piC), five out of six (for E_t) and four out of four (for GPP) models agree in sign.

ubiquitous increase in GPP with CO_2. While E_t shows only slight increases in tropical and most extra-tropical regions and no robust change in subtropical areas, the increase in GPP is associated with a strong increase in WUE, especially between piC and 4xCO_2. Decreases in WUE for parts of Central Asia between LGM and piC are related to stronger increases in E_t when compared to those in GPP. We note that the response in WUE is related to the well-known effect of CO_2 fertilization (e.g. Roderick *et al* 2015).

4.2.3. Soil moisture changes

Figure 4 qualitatively illustrates the direction of total soil moisture changes between (i) LGM and piC and (ii) piC and 4xCO_2 for all six models that provide soil moisture output. Declining soil moisture between LGM and piC is common among all models in the Mediterranean region, southern Africa as well as in parts of the Amazon basin, North America and East Asia, whereas robust increases in soil moisture are found in the northern high latitudes. Robust decreases (six out of six models) are evident in an even larger area within the Mediterranean region and southern Africa between piC and 4xCO_2. However, also for most parts of South America, North America and eastern Asia the majority of models (five out of six) project a SM decline. Uncertain changes (four, or less, out of six models) are primarily located in large parts of Africa, Australia and Asia.

In order to adequately assess regional changes in soil moisture in absolute terms, it is important to account for model-dependent differences in the absolute amount of water within the considered soil column. The absolute depths of the soil column are different, depending on the land surface model associated with each climate model. We therefore provide both maps of (i) mean-climatological SM for each equilibrium experiment and (ii) absolute SM-changes between experiments for each model individually in the supplementary information.

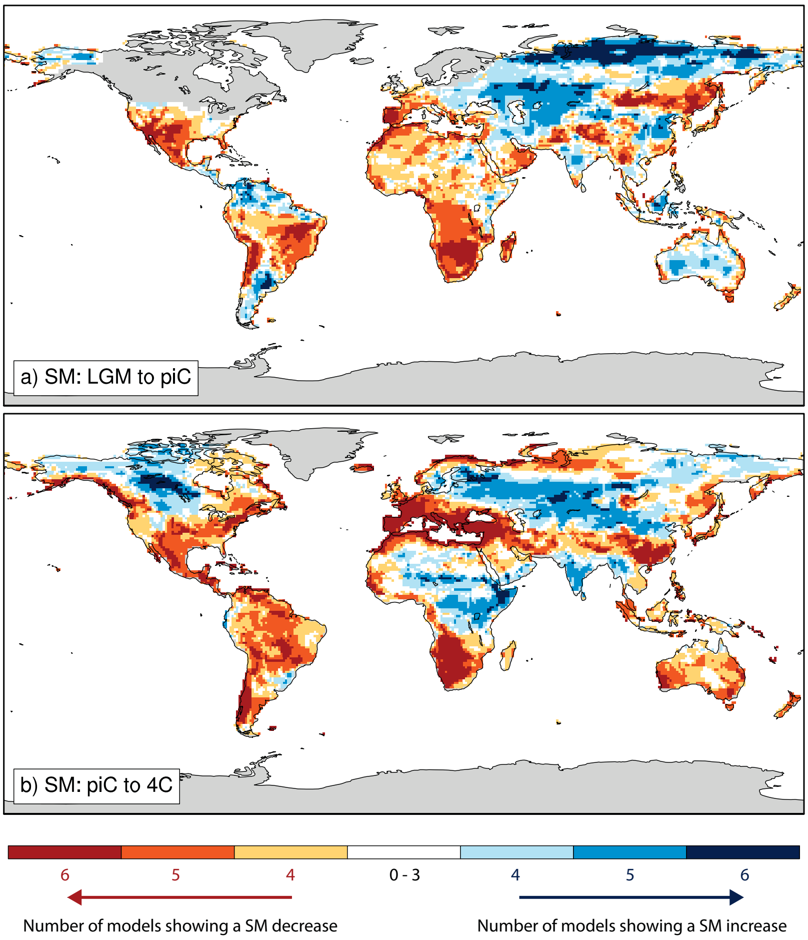

Figure 4. Direction of change in SM. Number of models showing an increase/decrease in SM between LGM-piC (top) and piC-4xCO_2 (bottom) for all six models providing SM estimates.

5. Summary and concluding remarks

To conclude, our results do in general not support the assumption of more arid conditions in a warmer world when assessing global terrestrial averages. We used a set of seven state-of-the-art climate models to assess changes of important variables of the hydro-climatological system as a function of CO_2. We also considered an agro-ecological viewpoint by additionally taking changes in GPP, E_t and WUE into account. The terrestrial water fluxes and agro-ecological quantities show lowest global averages under conditions of low atmospheric CO_2 prevailing under cold glacial conditions. As summarized in figure 5, increasing CO_2 does lead to dominating increases in GPP and *P*. Global averages in rH are mixed and model-dependent, but show decreasing tendencies between piC and 4xCO_2, which was also found in Fu and Feng (2014). On regional levels, decreases in SM are, however, more common than increases. The increase in GPP against only slight changes in E_t further results in an overall increase in WUE. Our findings hence imply that global averages of meteorological, hydrological, and agro-ecological *aridity* measures generally show decreasing *aridity* in the Earth system models as CO_2 (and *T*) increase, although results are more mixed for *atmospheric aridity* and *agricultural (soil moisture) aridity*—but also less pronounced than for the *aridity index* (figure 5).

How can we reconcile that finding with the earlier studies using more or less the same GCMs apparently projecting a strong tendency to increased *aridity* (Feng and Fu 2013, Sherwood and Fu 2014, Huang *et al* 2016, Scheff and Frierson 2015)? The key here is to recognise that our study used climate model output directly. Earlier studies used the same model output as the input to a secondary, offline, impact model: the *aridity index* model. Hence it is the *aridity index* approach that projects increasing *aridity* and not the climate models per se. We note that some of the key assumptions that underlie the *aridity index* model are incorrect when CO_2 is changing. One key assumption is that the minimum resistance for a wet surface remains constant over time and does not respond to CO_2. This assumption is reasonable for a lake or for wet soil. However, it is not applicable for vegetated surfaces because the minimum resistance is expected to respond (increase) to changes in CO_2 (Roderick *et al* 2015, Milly and Dunne 2016). In addition, stomatal resistance also increases when the available soil

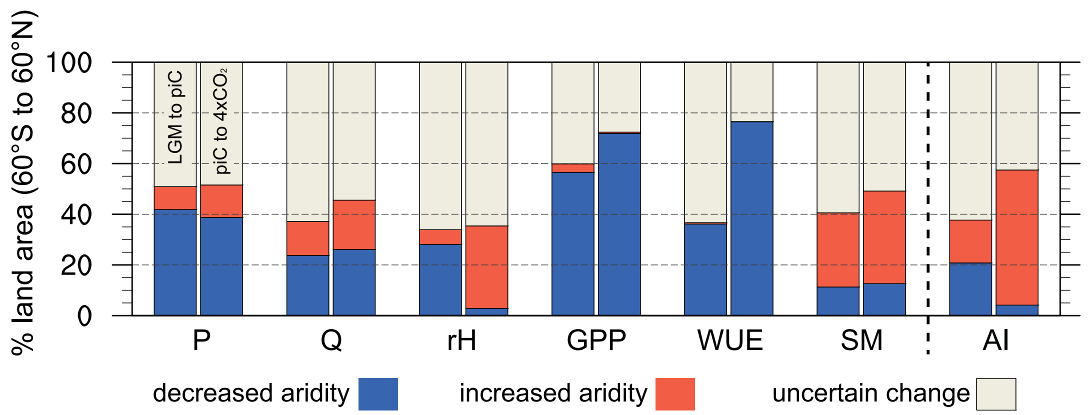

Figure 5. Percentage land area displaying changes in various aridity metrics within the 60° S–60° N domain. Increases (red), decreases (blue) or stable conditions (beige) are shown for changes in *P*, *Q*, rH, GPP, WUE, SM and the aridity index (AI) between (i) LGM and piC (left bar) and (ii) piC to 4xCO_2 (right bar). An increase/decrease was assigned if six out of seven models for *P*, five out of six models for *Q* and SM, four out of four models for rH, GPP and WUE (4 C-piC) and three out of three models for WUE (piC-LGM) and AI agreed in sign. It is important to note that for all variables an increase in the variable itself is associated with decreasing aridity.

moisture decreases, providing a negative feedback to soil drying under conditions of enhanced atmospheric demand (Seneviratne *et al* 2010, Swann *et al* 2016). We further like to point out that in this context the naming convention of the *aridity index* is indeed misleading and in fact not directly related to the common definition of *aridity*, i.e. a lack of moisture, as it conceptually represents something else: the interplay of atmospheric water demand vs. atmospheric water supply.

From a regional perspective, many areas are, however, projected to experience conditions of increased *aridity*. These areas are mainly located in subtropical regions and reveal consistent decreases in *P* and especially in *Q*. Nonetheless, even where *P* is projected to decrease, GPP is projected to increase. This arises because as CO_2 rises, the WUE generally (but not always) increases. In general, most tropical and mid to northern high latitude regions are projected to experience decreasing *aridity* over the 21st century due to positive changes in *P*, *Q*, GPP, WUE and SM.

It is important to take into account that in most regions the final conclusion on changes in *aridity* will depend on the metric choice. However, these results are based on climate model projections that are themselves subject to uncertainty and since most metrics are interrelated, uncertainty is additionally propagated between metrics (such as e.g. uncertain *P* projections will have implications for *Q*, *SM*, etc.). Most importantly, some terrestrial ecologists have been skeptical that the climate model projected increases in GPP reported here (figure 3) and elsewhere (Cramer *et al* 2001, Shao *et al* 2013) may not be realised because of nutrient constraints (Hungate *et al* 2003, Peñuelas *et al* 2011, Piao *et al* 2013) or changes in climate extremes (Reichstein *et al* 2013). Additionally, changing seasonal characteristics potentially have a strong influence on carbon fluxes (Murray-Tortarolo *et al* 2016). The stimulation of GPP by elevated CO_2 remains the subject of intense and ongoing research (Campbell *et al* 2017).

In conclusion, figure 5 reveals that climate model projections over a wide range of atmospheric CO_2 concentrations show *meteorological* (*P*, figure 2, figure 5) and *agro-ecological* (GPP, figure 2, figure 5) *aridity* decreases with CO_2 for the majority of the global land area. The situation for *hydrologic* (*Q*, figure 2, figure 5) and *agricultural aridity* (SM, figure 4, figure 5) is more nuanced with declines in *Q* projected to be almost as common as increases, and declines in SM projected to be more common than increases. Nonetheless, even for these latter variables the projected changes in *aridity* between piC and 4xCO_2 are not as strong as when assessed with the *aridity index* based on E_{ref} (maps of the *aridity index* are provided in the supplementary information).

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