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Model consensus projections of US regional hydroclimates under greenhouse warming

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Abstract

We investigate ensemble-mean ('consensus') values of resolution-weighted CMIP5 multi-model simulations of 1976–2005 summer regional hydroclimates, and of their projected 2070–2099 changes under three progressively more severe representative concentration pathways greenhouse scenarios. Uncertainties in these consensus values are estimated from the cross-ensemble scatter. We analyze differences among 30 year present-day and future consensus summer hydroclimates that are averaged over three disparate regions of the United States: the semi-arid Southern Great Plains, the arid Southwest, and the humid Southeast. Our study considers the impact of several scenarios of greenhouse forcing on the regional averages of both single hydroclimatic variables and on ratios of variables which are indicative of continental drying, as well as the partitioning of surface moisture or available energy into their respective subcomponents. In all three study regions, there is a projected robust increase in surface temperature as the severity of the greenhouse scenario increases; but the regional-average hydroclimatic changes are comparatively uncertain, and often are not proportional to the change in surface warming. There is, however, a projected robust increase in continental drying that is manifested by several complementary measures, but that differs in magnitude by region. The prospect of future continental aridification should be viewed with some caution, however, since it may be a result of various shortcomings in current-generation climate models or in the specified greenhouse scenarios.

1. Introduction

Disruptive changes in the continental hydrological climate are among the most concerning impacts that increased future greenhouse warming portends. While such impacts will be global in scale, they are likely to manifest themselves in diverse ways on smaller spatial scales: some regional hydroclimates may 'benefit' from greenhouse warming, while others may experience detrimental outcomes ranging from trivial to catastrophic.

From both a physical and a socio-economic perspective therefore, the hydroclimatic impacts of greenhouse warming will be experienced differently, depending on one's geographical location.

In some regions, the increases in surface temperature T that are anticipated under greenhouse warming may trigger significant changes in the interplay of

regional precipitation P , evaporation E , and runoff Q . The magnitudes of these hydroclimatic components, as well as their inter-relationships, may be altered substantially as greenhouse warming intensifies.

Simulations by coupled ocean-atmosphere global climate models (OAGCMs) are presently the main tools used for projecting future changes in hydrology, as well as in other large-scale aspects of the climate system. While regional climate models (RCMs) also are sometimes employed to study detailed impacts of prospective climate change on agriculture, water resources, energy systems, etc the RCMs depend on OAGCMs to furnish information of the time-dependent large-scale climate state at regional boundaries. OAGCM representations of hydroclimatic variables and relationships therefore remain critical for detailed studies of regional climate by RCMs. A large majority

of current-day OAGCMs providing simulations of historical climate and of prospective future climates have been organized under the auspices of CMIP5, the fifth phase of the Coupled Model Intercomparison Project (Meehl and Bony 2011, Taylor *et al* 2012). In part because of their relatively coarse horizontal resolution (a typical grid-box scale is about $2^\circ \times 2^\circ$ latitude/longitude), the CMIP5 model simulations display considerably more statistical uncertainty on regional scales than on continental-to-global scales (e.g. Intergovernmental Panel on Climate Change (IPCC) 2014, Goldenson *et al* 2018). However, this uncertainty can be reduced by considering the statistics of multi-model ensembles of climate simulations. By averaging a climate variable V across individual model simulations of historical climate, the resulting ensemble-mean $\langle V \rangle$ is often found to show closer agreement with observations of V than any single model simulation (e.g. Lambert and Boer 2001, Phillips and Gleckler 2006, Gleckler *et al* 2008). Christiansen (2018) offers a theoretical explanation for this empirical result that is based on the statistical properties of high-dimensional spaces, such as are realized by climate observations and simulations drawn from the same probability distribution.

Hence, our study adopts an ensemble-averaging approach in order to reduce the uncertainties of the CMIP5 simulations of summer hydroclimatic quantities over three diverse regions of the conterminous United States (CONUS): the semi-arid Southern Great Plains (SGP), the arid Southwest (SW), and the humid Southeast (SE).

In order to further reduce these uncertainties, we also consider *spatial averages* of the hydroclimatic quantities over these regions. This approach is a departure from typical analyses of regional climate change (e.g. Sheffield *et al* 2013, Intergovernmental Panel on Climate Change (IPCC) 2014, Maloney *et al* 2014, FNCA 2017), where differences between a two-dimensional present-day climate variable and its projection under a given climate-change scenario are mapped. However, this methodology makes it difficult to identify the impacts of greenhouse warming under several different scenarios, as well as the relationships between diverse hydroclimatic variables and the respective greenhouse-induced increases in temperature. By instead analyzing changes in *regional-average* hydroclimatic quantities, the impact of increasingly severe greenhouse warming on diverse aspects of regional hydroclimate can be conveyed using relatively few figures (e.g. Gedney *et al* 2000, Wartenburger, *et al* 2017, Seneviratne *et al* 2018).

It is the purpose of our study to document the present ensemble-mean ‘consensus’ of the CMIP5 global climate models on projected greenhouse-induced changes in hydroclimatic variables that are averaged over three hydroclimatically distinct US regions. In doing so, we also wish to acknowledge existing uncertainties and the ongoing scientific controversies

concerning the impacts of greenhouse warming on continental hydroclimate.

In section 2, we discuss details of the available CMIP5 model data and the analysis method. Salient results are presented in section 3, and interpretive remarks are offered in a concluding section 4.

2. Data and methods

2.1. Hydroclimatic quantities and their regional averages

Continental hydrology is subject to more regional control in summer, when soil moisture typically couples more strongly with the atmosphere (Koster *et al* 2006, Seneviratne *et al* 2010), and when extra-regional transports of heat and moisture are weaker than in other seasons (e.g. Nigam *et al* 2017; see also the discussion of moisture transports in section S2 of the supplementary material, available online at stacks.iop.org/ERL/14/014005/mmedia). The strength of land-atmosphere coupling also is expected to increase, especially in water-limited regions, under further greenhouse warming (Dirmeyer *et al* 2012). During summer also, vegetation photosynthesis and transpiration strongly influence the exchanges of water, energy, and carbon with the atmosphere (Running and Nemani 1988). Moreover, hydrological extremes such as droughts and floods are usually more acute in the summer season (Intergovernmental Panel on Climate Change (IPCC) 2007).

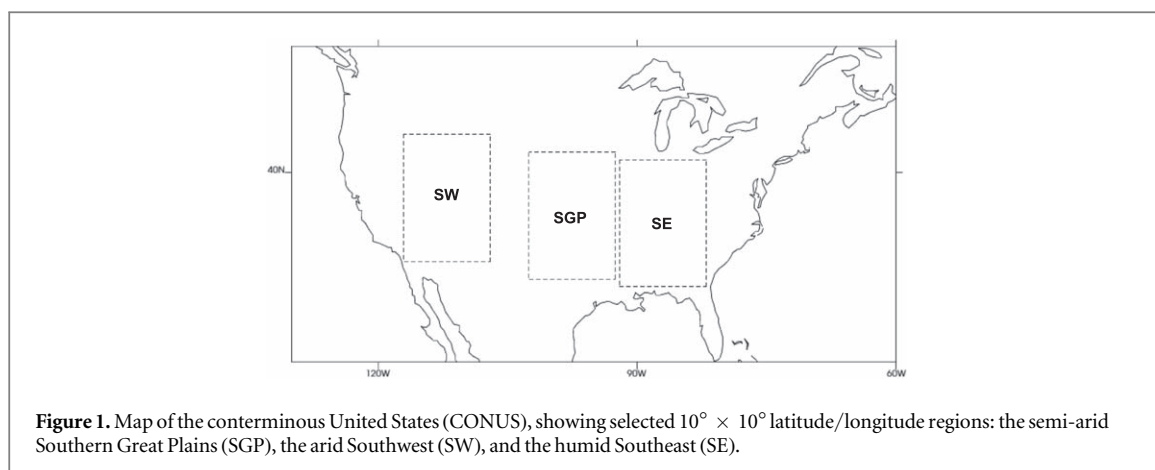
We therefore analyzed 30 year (1976–2005) boreal summer (June–July–August–JJA) climatologies of CMIP5 Historical climate simulations, and of (2070–2099) climate-change projections of regional hydrological quantities V . These 30 year climatological periods are roughly similar to those adopted by Sheffield *et al* (2013) and Maloney *et al* (2014) in their evaluations of CMIP5 simulations of North American Historical and projected future climatologies.

The individual variables we chose for investigation were surface air temperature T , precipitation P , total evaporation E (including both evaporation from bare ground and evapotranspiration by plants), and total runoff Q (including both surface runoff and gravitational drainage). We did not investigate other pertinent quantities such as surface atmospheric humidity because this was not provided by several of the CMIP5 models’ future-climate projections. We also did not analyze soil moisture because this model-specific quantity (see Koster *et al* 2009) was sensitive to the set of simulations/projections that were available for each numerical experiment (see table 1). Our choices of regional dryness and moisture/heat partition metrics (described below) were intended to compensate somewhat for the lack of model humidity and soil moisture data.

Other analyses of simulations of hydroclimatic impacts of global warming often focus mainly on single variables. However, it can be even more revealing of the hydrological impacts of simulated greenhouse

Table 1. Listing of the selected CMIP5 models, their institutional/country affiliations, their horizontal-grid resolution (expressed as the total number of latitude $\times$ longitude grid cells), and the climate simulations for each type of numerical experiment that were available from the PCMDI data archives (denoted by $\checkmark$).

Model version	Institution, Country	Resolution	Historical	RCP2.6	RCP4.5	RCP8.5
bcc-csm1-1-m	Beijing Climate Center, China Meteorological Administration	64 $\times$ 128	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
CNRM-CM5	Centre National de Recherches Meteorologiques/Centre European de Recherche et Formation Avancées en Calcul Scientifique, France	128 $\times$ 256	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation, in collaboration with the Queensland Climate Change Centre of Excellence, Australia	96 $\times$ 192	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University, China	60 $\times$ 128	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA	90 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
GFDL-ESM2M		90 $\times$ 144	$\checkmark$		$\checkmark$	$\checkmark$
GISS-E2-H	NASA Goddard Institute for Space Studies, USA	90 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
GISS-E2-R		90 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	96 $\times$ 96	$\checkmark$		$\checkmark$	$\checkmark$
IPSL-CM5A-MR		143 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	128 $\times$ 256	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies	64 $\times$ 128	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MIROC-ESM-CHEM		64 $\times$ 128	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	96 $\times$ 192	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
MPI-ESM-MR		96 $\times$ 192	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
NorESM1-M	Norwegian Climate Centre	96 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
NorESM1-ME		96 $\times$ 144	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
Total Simulation Sample Size			17	15	17	17



warming to investigate changes in how precipitation is partitioned into runoff versus evaporation, or how the net surface radiant energy is distributed into sensible versus latent heat components. Such distributive changes, which can be expressed in terms of dimensionless ratios, are indicative of *qualitative* changes in regional hydroclimate brought about by greenhouse warming. We therefore analyzed the partitioning of P into Q and E by means of runoff and evaporation efficiencies Q/P and E/P , and the partitioning of net surface radiation R_n into sensible versus latent heat fluxes S and L , by means of the efficiency ratios S/R_n and L/R_n (Budyko 1974, Koster 2015).

Finally, we employed a dryness index $DI = R_n/\lambda P$ (e.g. Koster and Suarez 1999, McColl *et al* 2017), where λ is the latent heat of vaporization. DI measures the extent to which a greenhouse-induced increase in regional R_n , promoting enhanced dryness, is offset by an increase in P . Since R_n is the total available energy at the land-atmosphere interface, it may be viewed as an *upper bound* on the potential evaporation E_p from a saturated, vegetation-covered surface. DI thus is reminiscent of Budyko's aridity index E_p/P (Budyko 1974). However, although R_n is thought to be the most important contributor to the spatial variability of potential evapotranspiration (Sheffield *et al* 2012), E_p is also influenced by the surface atmospheric humidity, as well as by the moisture conductance of vegetation stomates which is typically set to a fixed value (Penman 1948, Monteith 1973). Because the CMIP5 models did not supply their simulated values of E_p , and several selected models also did not provide the simulated values of surface atmospheric humidity required for calculating E_p , we used index DI as a practical alternative indicator of the drying effects of greenhouse warming.

In order to further reduce uncertainties beyond that afforded by computing a cross-model ensemble mean, we area-averaged all the chosen hydroclimatic quantities over $10^\circ \times 10^\circ$ regions within three hydrologically diverse US regions: the semi-arid SGP, the arid SW, and the humid SE—see figure 1. (The central point for the SGP region is 36.6° N and 97.5° W, that for

the SW region is 38.0° N and 112.0° W, and that for the SE region is 36.0° N and 87.0° W.)

The chosen study regions display qualitative differences in current hydroclimate, and were selected mainly because they are expected to respond quite differently to future greenhouse warming. (Note that the chosen regions do not include especially large US population or economic centers, which might serve as different regional selection criteria for alternative studies of greenhouse-warming impacts.) The SGP is a region of large interannual variability, with alternating dry or wet summer conditions, depending in part on the amount of atmospheric moisture transported from the Gulf of Mexico. The hydroclimate of the SGP region also depends on the intensity of the nocturnal low-level Jet to the west, which triggers precipitating convective cells that propagate over the SGP region (Weaver and Nigam 2008). The arid SW US is distinguished by rugged, complex topography, so that the timing of runoff from snowmelt will likely be impacted by future greenhouse warming (Li *et al* 2017). In addition, precipitation triggered by the North American Monsoon plays an important role in the summer SW hydroclimate (Adams and Comrie 1997). In contrast, the humid SE US typically receives plentiful precipitation throughout the year, but with a climatological warm season maximum that is related to vigorous convective storms and landfalling hurricanes (NCCO 2010). Unlike the SGP and SW regions, therefore, the SE US usually does not generally display the characteristics of a moisture-limited hydroclimate, even though it is subject to occasional droughts (Seager *et al* 2009).

In all three study regions, $10^\circ \times 10^\circ$ latitude/longitude areas (unlike $3^\circ \times 3^\circ$ - and $5^\circ \times 5^\circ$ patches) yielded JJA area-averaged means of hydroclimatic quantities that were usually more than ten-times their inter-annual standard deviations in a 30 year CMIP5 simulation. (The main exception was the highly intermittent runoff Q , whose typically low JJA mean value was only a few times larger than its inter-annual standard deviation in each region.)

Regional averages of the hydroclimatic efficiencies and the dryness index may be computed in two ways: as (1) a spatial average of a hydroclimatic ratio (e.g. $\langle E/P \rangle$) over the region, where $\langle \rangle$ denotes regional averaging, or as (2) a ratio of regional averages of two variables (e.g. $\langle E \rangle / \langle P \rangle$). We investigated both methods of regional averaging, and found that their respective JJA climatologies were fairly similar. However, for an individual climate model, the type-2 regional averaging generally showed less inter-annual variability in individual JJA samples, and hence, less uncertainty in the model's corresponding JJA climatologies, than did the alternative type-1 averaged ratio. Our results, presented in section 3, thus reflect use of type-2 calculations of hydroclimatic ratios.

2.2. Greenhouse warming scenarios and model simulations

For CMIP5 simulations, greenhouse warming scenarios are expressed as successively more severe representative concentration pathways (RCP) 2.6, 4.5, 6.0, and 8.5 (Meinshausen *et al* 2011, Collins *et al* 2013). The RCP numbering scheme pertains to the year-2100 global surface radiative forcings of, respectively, 2.6, 4.5, 6.0, and 8.5 W m^{-2} above that of a preindustrial greenhouse forcing level. Each scenario also includes different land-use and socio-economic assumptions, resulting in expected peak greenhouse emissions at different times. Scenario RCP2.6 assumes that emissions peak between 2010–2020, RCP4.5 around 2040, and RCP6.0 in the latter decades of the 21st century. For RCP8.5—sometimes referred to as a ‘business-as-usual’ scenario—greenhouse emissions are assumed to continue rising throughout the entire century (see figure S1 in the supplementary material). Note that, because substantially fewer CMIP5 models supplied simulations of RCP6.0 than for the other scenarios, investigation of the RCP6.0 climate-change projections is not included in this study.

For the analysis of hydroclimatic projections under greenhouse warming, we *arbitrarily* selected a single resolution (designated as realization ‘r1i1p1’) from each of the available CMIP5 model simulations, according to the following criteria: 30 year time series of monthly values of all requisite hydroclimatic quantities were available for the 1976–2005 Historical climate simulation, and for at least two of the three RCP scenarios 2.6, 4.5, and 8.5 over the period 2070–2099, when all of the associated emissions trajectories become well-separated (see figure S1). We thus did *not* choose model realizations according to normative criteria such as their goodness-of-fit with historical climate observations. While alternative criteria for selecting model realizations are popular topics for current research, today's climate modeling groups instead seem motivated to generate larger *numbers* of realizations for better estimation of simulation statistics (see also section 4).

The CMIP5 models meeting our selection criteria are listed in table 1, along with their institutional/national origins and horizontal-grid resolutions. For further details on the characteristics of individual CMIP5 models, see Flato *et al* (2013).

2.3. Model consensus estimates and their uncertainties

Because a higher-resolution simulation yields more samples of the $10^\circ \times 10^\circ$ study areas than does a lower-resolution one, we weighted each simulation according to the associated model resolution, as follows. An initial weight $w(i)$ for each simulation i was calculated as a ratio of the corresponding horizontal resolution $r(i)$ (expressed as a product of latitude-longitude grid values, as shown in table 1) to the maximum resolution $R_{\max}$ for each ensemble of Historical or RCP scenario simulations:

$$w(i) = r(i) / R_{\max}.$$

For instance, $w(i) = 1$ is assigned to a model with the finest spatial resolution, and $w(i) = 0.5$ to a model with a spatial resolution that is twice as coarse. These initial weights then were normalized across the N simulations in each ensemble

$$W(i) = w(i) / \sum_{i=1}^N w(i)$$

so that

$$\sum_{i=1}^N W(i) = 1.$$

For each ensemble, we then computed a resolution-weighted, multi-model mean (*MM*) value of each regional hydroclimatic quantity $V(i)$ as

$$MM = \sum_{i=1}^N W(i) * V(i).$$

The *MM* value may be thought of as a model ‘consensus’ estimate of a hydroclimatic quantity. Note from table 1 that $N = 17$ simulation samples make up the *MM* values for the Historical climate and for the RCP4.5 and RCP8.5 scenario experiments, while $N = 15$ simulation samples make up the *MM* value for the RCP2.6 scenario.

Uncertainty in the *MM* consensus value, which is associated with the intra-ensemble scatter of the simulations, arises from both *internal* and *structural* variability. Internal variability reflects the chaotic characteristics of climate predictions, owing to the sensitivity of simulated climate variables to initial conditions, which differ somewhat across the CMIP5 models. Structural variability reflects the differences in model representations of physical processes that determine the simulated climate variables. In addition, some of the intra-ensemble scatter (especially in simulations of Historical climate) results from different specifications of radiative forcings (e.g. those associated with anthropogenic or volcanic aerosol concentrations) in the CMIP5 models.

From statistical sampling theory, we estimated the magnitude of the uncertainty U in the MM values of each hydroclimatic quantity V by dividing the standard deviation s of the intra-ensemble scatter about each MM value by the square root of the number of CMIP5 simulations N that were available for each experiment (see table 1):

$$U = s/(N)^{1/2},$$

where s is a resolution-weighted quantity (see DATAPLOT Reference Manual 1996) estimated as:

$$s = \left\{ \sum_{i=1}^N W(i) * [V(i) - MM] / \left[(N-1) \sum_{i=1}^{N^2} W(i)/N \right] \right\}^{1/2}.$$

However, because structural similarities exist among the models (especially for alternative model versions from the same institution—see table 1), the simulation samples making up each MM value are not statistically independent (Knutti *et al* 2013, 2017). The uncertainty U of an MM value thus should be regarded as only a rough estimate of the actual uncertainty (Steinschneider *et al* 2015). U nonetheless conveys a sense of the *relative* uncertainty of the MM value for each simulated hydroclimatic quantity.

The weighting of the CMIP5 simulations by model resolution did not greatly alter the consensus or uncertainty estimates obtained by unweighted averaging, but there were some discernible quantitative impacts. For example, in certain instances a small positive (negative) change in an unweighted consensus value across RCP scenarios would be rendered as a small negative (positive) resolution-weighted change.

3. Results of model consensus simulations

To discern the relationships between regionally specific hydroclimatic quantities under diverse greenhouse RCP scenarios, their regional-average MM consensus values are displayed on x – y plots that correspond to the Historical climate simulation (denoted as ‘H’) and to the three selected RCP greenhouse scenarios (denoted as ‘2.6’, ‘4.5’, and ‘8.5’). In addition, the estimated uncertainties of the MM values of the plotted variables are denoted by crossing horizontal and vertical error bars (for example, see figure 2).

3.1. Projected relationship of precipitation and surface temperature

Figure 2 shows the relationships between MM values of regional-average precipitation P and surface temperature T for the simulated 1976–2005 Historical JJA climatologies, and for their 2070–2099 projections under the three RCP greenhouse scenarios RCP2.6, RCP4.5, and RCP8.5.

The simulated Historical MM value for each regional average of JJA climatological P and T (denoted by ‘H’) can be compared with the corresponding observational estimates (after the Climatic Research Unit

observations described by Harris *et al* 2014). The simulated consensus Historical (‘H’) estimates of regional P and T match the respective observations (denoted by diamonds) fairly well, confirming the efficacy of our weighted ensemble-averaging methodology.

Simulation biases differ somewhat by region, however. The consensus Historical climate of the humid SE region is a little warmer and wetter than observed (298 K, 3.6 mm d^{−1}). In the arid SW, the consensus simulation of Historical T is very close to observations (294 K), while simulated P is a bit too high (1.1 versus 0.86 mm d^{−1}). In the semi-arid SGP region, simulated Historical T and P are warmer and drier than the observations (299 K, 2.8 mm d^{−1}), due to a known systematic bias in the CMIP5 Historical summertime simulations that is attributable to errors in both simulated atmospheric forcings and land responses (Cheruy *et al* 2014, Y Lin *et al* 2017).

The regional MM consensus projections of P for the three RCP greenhouse scenarios (denoted as ‘2.6’, ‘4.5’, and ‘8.5’, respectively) also are displayed in figure 2. For all three regions, T increases with the severity of the greenhouse scenario, showing an overall H → RCP8.5 change of about 5–6 K above the value of the consensus Historical simulation.

Regional precipitation varies in a more complex way, however. In the SGP region, consensus projections of P monotonically decrease with increasing warming, but change by different amounts across the climate-change scenarios (that is, the slope $\Delta P/\Delta T$ changes with RCP scenario). The largest decreases in P are found in the transitions RCP2.6 → RCP4.5 and RCP4.5 → RCP8.5, with much less change occurring in the H → RCP2.6 transition. Such nonlinear changes in P relative to T may result from climatological variations in the intensity or position of rain-producing atmospheric circulation features.

Cheruy *et al* (2014) and Lin *et al* (2017) point out that CMIP5 models with Historical climate simulations displaying the largest warm/dry biases relative to observations in the Central US also show the most warming and drying in the RCP-scenario simulations. We also identify such a tendency in the CMIP5 model simulations of T and P in the SGP region, suggesting that simulation of this regional hydroclimate is especially sensitive to model deficiencies in representing surface net radiation and land hydrology (Ma *et al* 2018, Morcrette *et al* 2018, Van Weverberg *et al* 2018, Zhang *et al* 2018).

In the SW region, however, only very small positive or negative consensus changes in P occur across the simulations. In the SE region also, there is only a very slight overall H → RCP8.5 increase of about 0.1 mm d^{−1} in the projected value of P , with almost all of the change occurring in the H → RCP2.6 transition.

The variation of ensemble-means of individual JJA values of P versus T are shown for each study region and for each model experiment (1976–2005 Historical

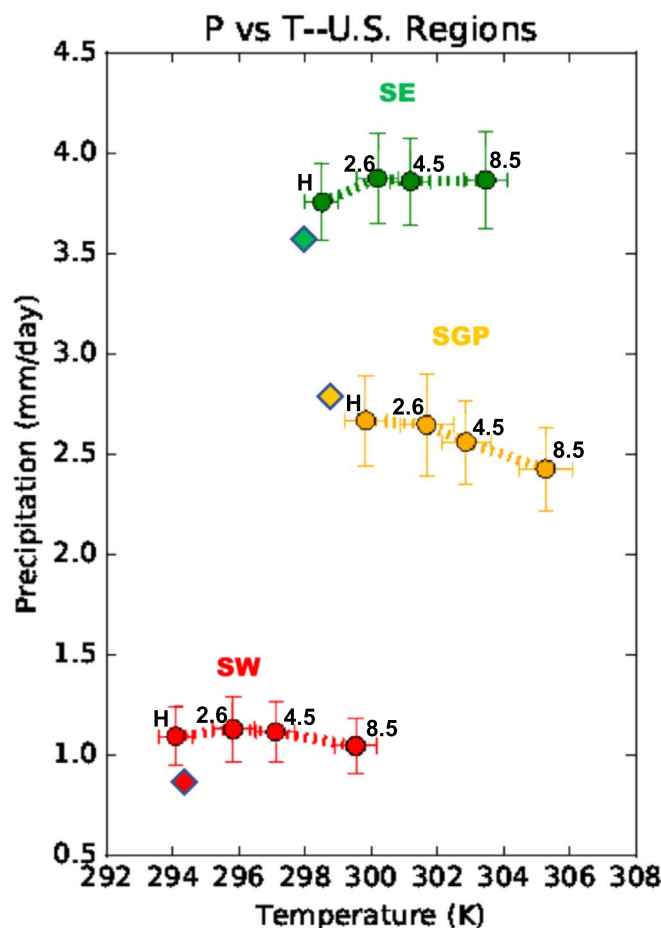


Figure 2. The relationship of regional-average precipitation P and surface temperature T for Historical and projected future June–July–August (JJA) climatologies in the Southern Great Plains (SGP, orange), the Southwest (SW, red), and the Southeast (SE, green) regions of the US. The dots indicate each region’s CMIP5 resolution-weighted ensemble multi-model mean (MM) consensus estimates of 1976–2005 June–July–August Historical climatology (‘H’) and of their 2070–2099 projections for the successively more severe RCP2.6 (‘2.6’), RCP4.5 (‘4.5’), and RCP8.5 (‘8.5’) greenhouse scenarios. The dotted lines trace trajectories between the scenarios, and the diamonds (following each region’s color scheme) signify the corresponding observed 1976–2005 JJA climatologies of P and T (after Harris *et al* 2014). The horizontal and vertical error bars indicate estimated uncertainties in each region’s hydroclimatic variables, based on the resolution-weighted, collective standard deviation of the model simulations from corresponding MM values.

climate and the three 2070–2099 RCP scenarios) in figure 3. Because the 2070–2099 RCP scenario trajectories are well-separated from one another and from the Historical climate state (see figure S1), there are distinct clusters of individual JJA values of P and T . (Note that the centroid of each P – T cluster in figure 3 corresponds to the 30 year climatological JJA MM values shown in figure 2.) In each cluster, P correlates negatively with T —a well-known observational relationship (Madden and Williams 1978, Trenberth and Shea 2005, Adler *et al* 2008). The P – T anticorrelation is thought to be a result of the strong coupling of summertime soil moisture with precipitation, where surface sensible heat flux and temperature increase as soil moisture is depleted (Berg *et al* 2015). It is seen that the clusters of negative P – T correlation are more well-defined for the SE and SGP regions than for the SW, presumably because precipitation couples less strongly with the reduced soil moisture in this arid region (Koster *et al* 2006). For the RCP8.5 scenario, the P – T anticorrelation also becomes less coherent in all three

regions, suggesting that a general change in hydroclimatic regime may be projected under this ‘business-as-usual’ greenhouse forcing.

In all the study regions of figure 2, the horizontal error bars denoting uncertainties in MM values of the regional-averages of T for different greenhouse scenarios do not overlap very much with one another. This implies that the increases in consensus estimates of T across the scenarios, and especially the overall H → RCP8.5 increase in regional-average T , is statistically robust. By contrast, the vertical error bars denoting uncertainty in the MM values of P across the greenhouse scenarios overlap much more with one another, implying that the corresponding changes in the projections of P are substantially less certain than the T projections. As the presentation of our other results will show, the greater degree of uncertainty for MM values of hydroclimatic quantities compared with those for surface temperature is a persistent pattern in all three study regions.

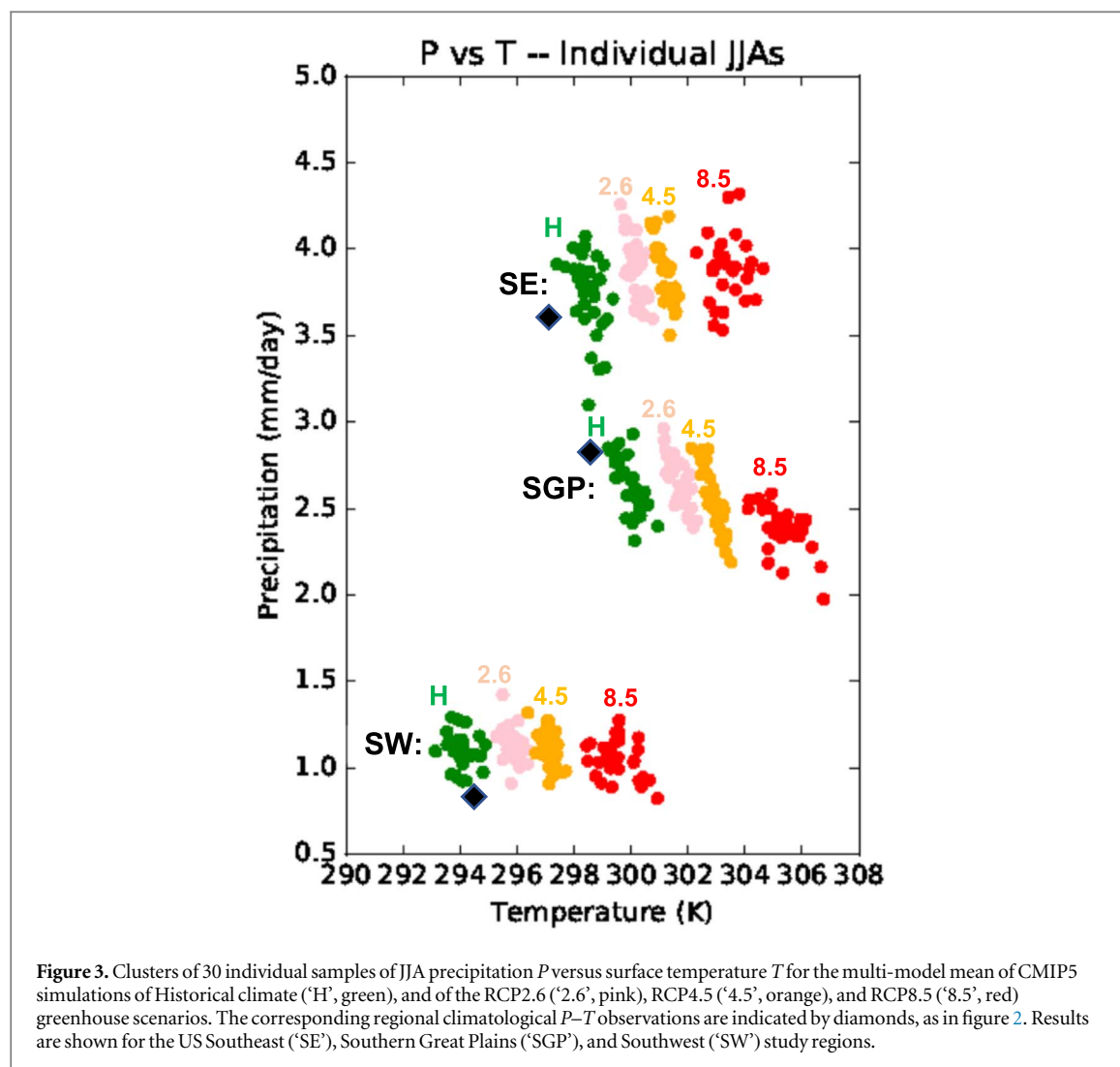


Figure 3. Clusters of 30 individual samples of JJA precipitation P versus surface temperature T for the multi-model mean of CMIP5 simulations of Historical climate ('H', green), and of the RCP2.6 ('2.6', pink), RCP4.5 ('4.5', orange), and RCP8.5 ('8.5', red) greenhouse scenarios. The corresponding regional climatological P - T observations are indicated by diamonds, as in figure 2. Results are shown for the US Southeast ('SE'), Southern Great Plains ('SGP'), and Southwest ('SW') study regions.

Table 2. Kolmogorov–Smirnov estimation of probabilities p (minimum 0, maximum 1) that the CMIP5 model ensemble mean samples of 30 JJA seasons for the H and RCP8.5 simulations of regional precipitation and dryness index are drawn from the same probability distribution. (The lower the p value, the less likely that the H and RCP8.5 samples are drawn from the same probability distribution.)

Hydroclimatic quantity	SGP region	SW region	SE region
Precipitation P	$p = 4.6 \times 10^{-6}$	$p = 0.055$	$p = 0.11$
Dryness index DI	$p = 2.6 \times 10^{-7}$	$p = 2.8 \times 10^{-3}$	$p = 4.6 \times 10^{-6}$

To state this point somewhat differently, the overall $H \rightarrow RCP8.5$ change in a regional hydroclimatic variable ΔV often does not exceed the average $H \rightarrow RCP8.5$ uncertainty U , so that the regional signal-to-noise ratio $\Delta V/U$ is less than 1. Hence, from the standpoint of a conventional Student's t -test of differences in the H and RCP8.5 mean values, the greenhouse-induced regional change ΔV is not statistically significant. However, application of the Kolmogorov–Smirnov (K–S) statistical test (e.g. Press *et al* 1987) to the distribution of 30-member ensemble mean JJA climates from which the MM values for the H and RCP8.5 simulations are calculated (e.g. see figure 3), provides estimates of the probability p that the H and

RCP8.5 samples are drawn from the same distributions (see table 2). Application of the K–S statistical test to the 30-member samples of JJA for the H and RCP8.5 simulations indicates that, for the SGP region, it is highly unlikely ($p = 4.6 \times 10^{-6}$) that the respective samples of P are drawn from the same probability distribution, while for the SW ($p = 0.055$) and especially for the SE regions ($p = 0.11$), we are less justified in rejecting this null hypothesis.

The large uncertainties that are inherent in model-based studies of regional greenhouse-induced hydroclimatic change motivate alternative methods for demonstrating the statistical robustness of results. For instance, other regional studies often indicate the

regions of a continent where there is *simulation consistency*, in the sense that a majority of the multi-model climate simulations show the same *sign* of a projected climate change. Having calculated resolution-weighted consensus MM values for different greenhouse scenarios, we instead will emphasize the *physical consistency* of several different hydroclimatic measures of dryness. This consistency (discussed in sections 3.2, 3.3, and S1) argues for the robustness of the main conclusion of our study: that projected greenhouse warming induces continental aridification, albeit to different degrees, in all three of our US study regions.

3.2. Projected relationship of dryness index and temperature

A region's susceptibility to future drying depends not only on how precipitation changes under greenhouse warming, but also on the associated changes in surface evaporation. The dryness index $DI = R_n/P$ is a measure of the relative magnitude of atmospheric moisture demand (R_n is an upper bound for potential evaporation E_p —see section 2.1 discussion) versus moisture supply P .

Plots of model consensus MM values of DI relative to greenhouse-warmed surface temperature T are shown for each study region in figure 4. Under increasing greenhouse warming, there is an overall $H \rightarrow RCP8.5$ increase in DI projected for transitions in all three study regions. This is because the greenhouse-induced increases in R_n (and in surface temperature and evaporation) are not offset by commensurate increases in precipitation P in any of the study regions (Fu and Feng 2014, Sherwood and Fu 2014). In addition, land-atmosphere feedbacks may amplify continental aridification (Berg *et al* 2016). The greenhouse-induced increases in dryness index DI are also consistent with other CMIP5 studies climate (Dai 2013, Seager *et al* 2013, Cook *et al* 2014, 2015; Lin *et al* 2015; Scheff and Frierson 2015; Huang *et al* 2016; Bonfils *et al* 2017; Herrera-Estrada and Sheffield 2017), which use a variety of dryness measures to identify an increasing propensity for continental aridity in projections of greenhouse-warmed 21st century.

The amount of the projected aridification varies considerably by region, however. In the semi-arid SGP, the overall $H \rightarrow RCP8.5$ increase in DI is about 0.7 above its Historical baseline (~ 2.8). Starting from a much higher Historical level of ~ 7.0 in the arid SW region, DI increases to a maximum of about 7.5. In the humid SE region, however, DI starts at a comparatively low Historical level of ~ 1.8 and rises only slightly higher (~ 1.9) for the RCP8.5 scenario.

The variation of DI across the series of warming scenarios also differs regionally. In the SGP and SE regions, dryness increases for each successive RCP scenario; but in the SW region, DI increases markedly only for the RCP4.5 $\rightarrow$ RCP8.5 transition, another indication that the RCP8.5 'business as usual' scenario

may induce the SW regional hydroclimate to enter a qualitatively different regime. This supposition is corroborated by K–S statistical tests (see table 2) which indicate that for all three study regions it is highly unlikely that the 30 JJA-samples of DI for the Historical and the RCP8.5 scenario are drawn from the same probability distribution.

3.3. Projected relationship of sensible heat efficiency and temperature

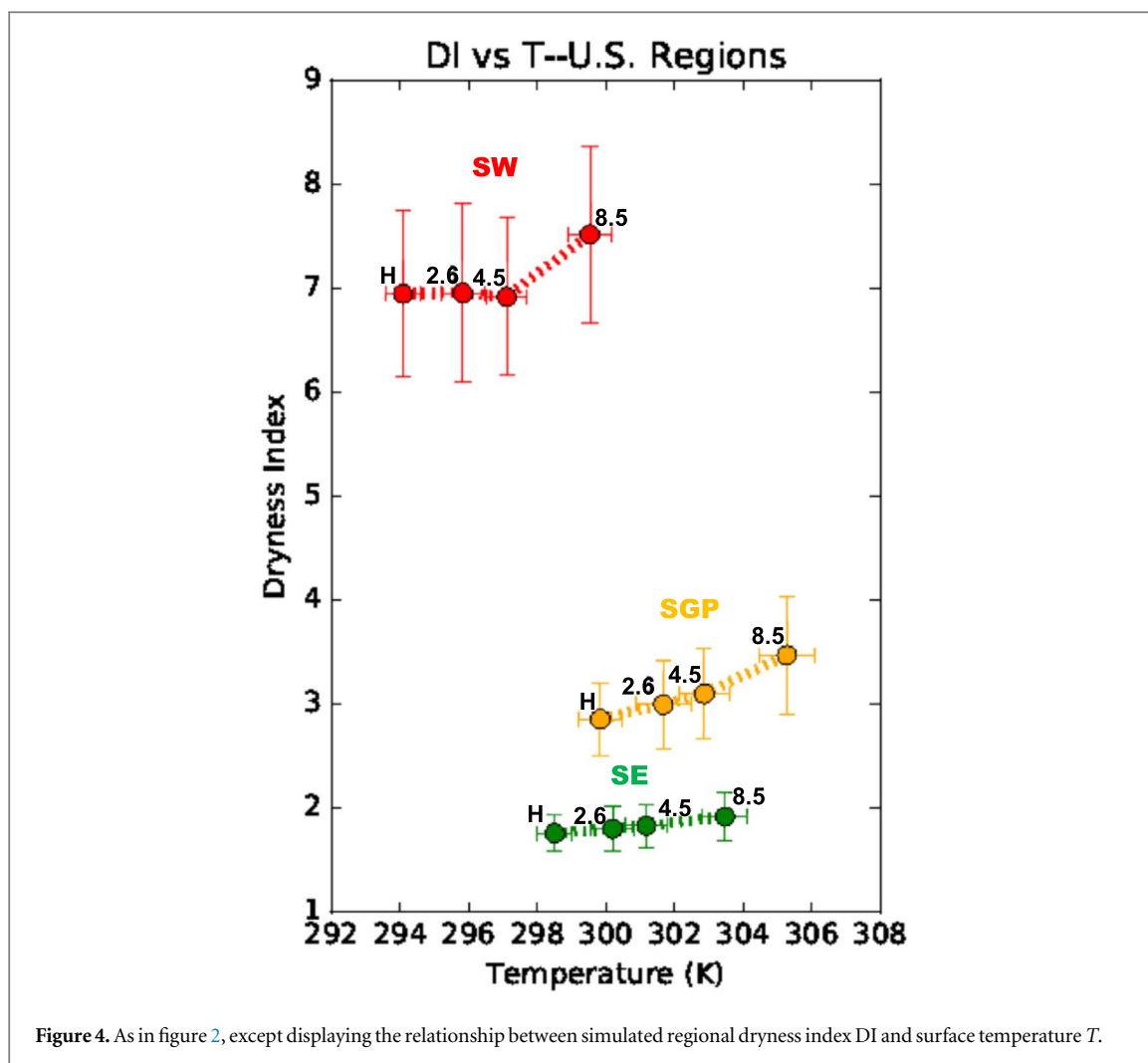
Increasing greenhouse forcing results in enhanced net surface radiation R_n , which is approximately equal to the sum of sensible and latent heating $S + L$, if the relatively small ground heat flux component is neglected. Increases in the sensible heat efficiency S/R_n are associated with decreases in latent heat efficiency L/R_n (since $L/R_n \sim 1 - S/R_n$) and a reduction in the moisture available for latent heating (e.g. Cai *et al* 2016).

The relationships between MM consensus values of regional-average sensible heat efficiency S/R_n and surface temperature T for the simulated Historical (1976–2005) JJA climatologies, as well as their 2070–2099 projections under the RCP2.6, RCP4.5, and RCP8.5 greenhouse scenarios, are shown for each study region in figure 5. It is seen that progressive increases in greenhouse forcing tend to promote increased sensible heat efficiency in all regions. This induces an overall increase in the Bowen ratio $B = (S/R_n)/(L/R_n)$, implying increasing regional dryness. However, the magnitude of the overall $H \rightarrow RCP8.5$ increase in S/R_n varies by region: ~ 0.06 for SGP, ~ 0.02 for SW, and ~ 0.04 for SE.

These changes occur in the presence of considerable inter-ensemble uncertainty; but they are physically consistent with the drying impact of greenhouse warming implied by figure 4. Plots of model consensus projections of relationships of other hydroclimatic quantities which supply complementary information on the projected regional drying impacts of greenhouse warming are shown in figures S2 and S3 of the supplementary material. For instance, the relationship of regional evaporative efficiency E/P versus T (figure S2) is very similar to that presented by the plots of the drying index DI versus T in figure 3. In addition, overall $H \rightarrow RCP8.5$ increases in moisture divergence ($E - P$) versus T (figure S3) also reinforce the conclusion that the SGP region is especially at risk of future greenhouse-induced aridification.

4. Concluding remarks

In this study we investigated projected JJA climatological relationships among selected hydrological quantities in three diverse US regions, under progressively more severe 21st century greenhouse-warming scenarios. The projected JJA climatologies, averaged over



$10^\circ \times 10^\circ$ areas centered on the semi-arid US SGP, arid SW, and humid SE regions, were obtained from ensemble MM values generated by 15–17 available CMIP5 simulations.

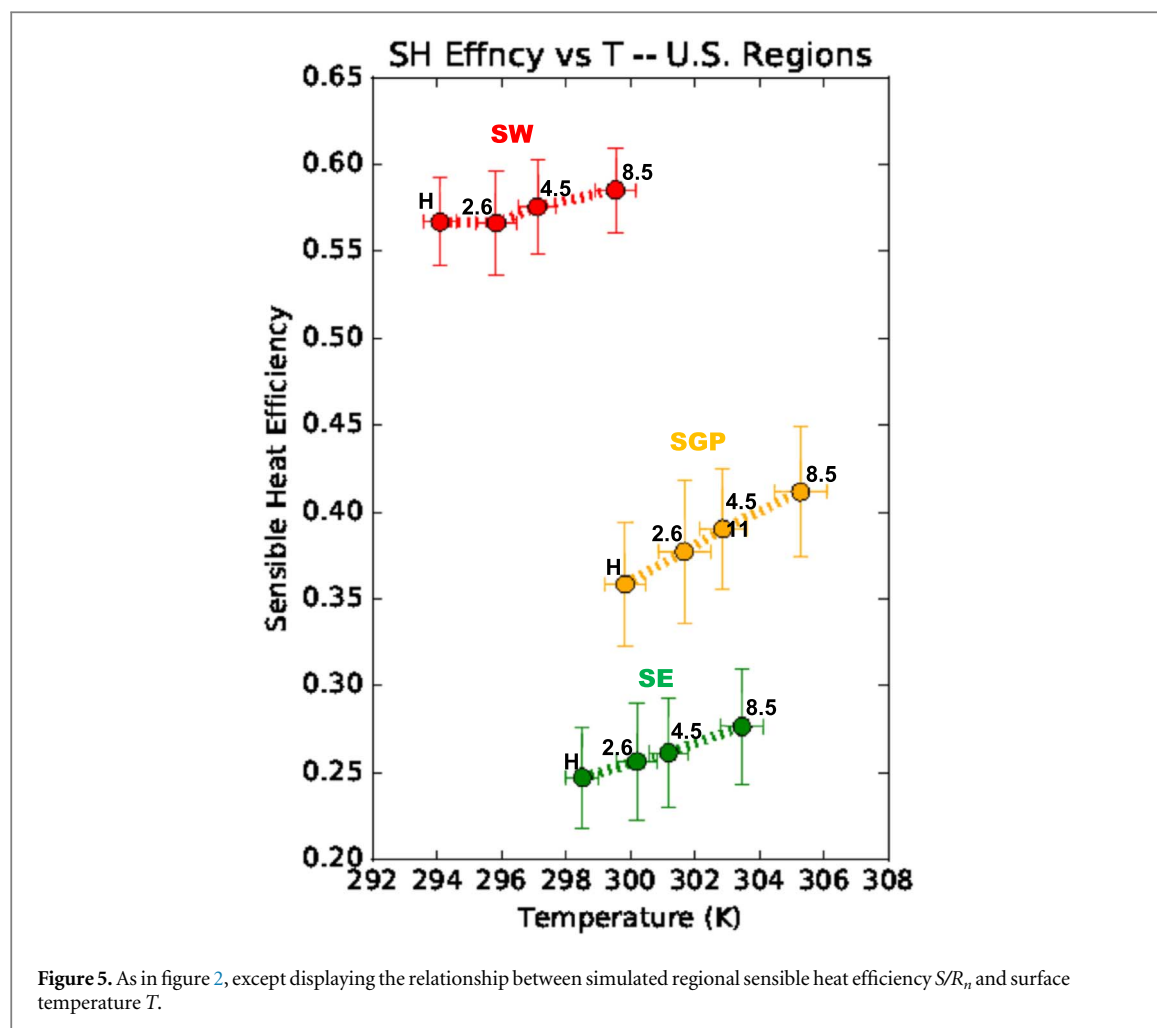
The plotted changes in regional MM values also convey a sense of the projected overall changes to be expected in these regional hydroclimates under increasing greenhouse warming. By spatially averaging simulated hydroclimatic quantities over these regions, and by resolution-weighted averaging of individual simulations of these quantities, we were able to reduce the climatic uncertainties relative to those present at grid scale in individual model simulations. Uncertainties in the MM values then were roughly estimated from the inter-ensemble spread of the individual model simulations about MM .

Results of this study imply several summary points:

- (1) Projected hydroclimatic changes are not generally proportional to the change in surface warming. For instance, the slope of the change in the MM consensus value of regional P per degree Kelvin increase in surface temperature T varies with transitions between specific greenhouse scenarios.

- (2) In all three study regions, there is a robust increase in surface temperature T as the severity of the greenhouse scenarios increase. There is also a general increase in drying manifested by increases in the dryness index DI , the sensible heat efficiency S/R_m , and the evaporative efficiency E/P , irrespective of whether decreases in regional precipitation P are also projected. Although the uncertainties associated with these complementary indicators are quite large, their physical consistency bolsters the plausibility of a projected generalized greenhouse-induced drying in the continental US.
- (3) The magnitude of the projected drying increase differs considerably by region, however. The greatest overall future drying is projected for the semi-arid SGP region, and the least for the humid SE region. However, it should be emphasized that the accuracy of the projected magnitudes of regional drying are limited by the associated large uncertainties in hydroclimatic quantities.

A projected general increase in US regional dryness should be regarded with some caution, however.



Ficklin *et al* (2016), for example, warn that CMIP5 Historical simulations display substantial biases in CONUS Historical precipitation P and potential evaporation E_p that are likely to produce overestimated future projections of Budyko's aridity index $AI = E_p/P$. Our use of a dryness index $DI = R_n/\lambda P$ as a rough approximation of E_p/P (see section 2.1) also neglects offsetting reductions in potential evapotranspiration E_p that may result from physiological changes in plants under greenhouse warming. That is, under enhanced atmospheric CO_2 , a reduction in stomatal conductance and increased water- and light-use efficiency by plants are anticipated. These vegetation effects may substantially offset future increases in potential evaporation (Berg *et al* 2016, Milly and Dunne 2016, Swann *et al* 2016, Bonfils *et al* 2017, Skinner *et al* 2017, Lemordant *et al* 2018, and Li *et al* 2018). H Yang *et al* (2018) also note that the future runoff Q projected by a subset of the CMIP5 models that include these vegetation effects generally increases, relative to current observational values. They attribute this projected overall increase in Q to decreased retention properties of catchments associated with increased incidences of greenhouse-induced precipitation extremes. Roderick *et al* (2015) and

Y Yang *et al* (2018) also point out a general propensity for enhanced future runoff. The CMIP5 ensemble-mean projections of increasing dryness under future greenhouse warming (figure 4) thus may not actually translate into universal decreases in regional water availability, as indicated by projected runoff amounts.

On the other hand, there are some reasons to be skeptical of the potential for vegetation-related mitigation of the drying impacts of greenhouse warming. For instance, by comparing the climate projections of those CMIP5 models that simulate a plant physiological response with those that do not, Dai *et al* (2018) conclude that the drying effect of greenhouse-induced warming is likely to overwhelm the wetting effect of plant physiology. In addition, Huntingford *et al* (2017) note that plant respiration of carbon dioxide may contribute more to atmospheric greenhouse gas concentrations than previously assumed, resulting in even higher projected surface temperatures and greater increases in atmospheric evaporative demand. Douville and Plazzotta (2017) and Seager *et al* (2018) also point out that the CMIP5 models collectively underestimate present-day US continental drying, and that the CMIP5 projections of future greenhouse-induced aridification may be underestimated. In

addition, future changes in land use/land cover also may have a deleterious impact on regional hydroclimates (e.g. Davies-Barnard *et al* 2014, Alexandru 2018), but these effects are not fully accounted for by the RCP greenhouse scenarios.

Thus, the amount of future US regional aridification to be expected under 21st century greenhouse warming is currently the focus of a highly contentious debate. This scientific controversy demands further detailed investigation, employing both field observations and next-generation climate models that can more realistically represent the impacts of vegetation and circulation dynamics on continental aridification.

Our study (among many others) also demonstrates the difficulty of obtaining accurate model projections of regional hydroclimate, given the large uncertainties in the quantities of interest, as simulated by today's climate models. Nevertheless, future advances in computing power should mitigate this difficulty in several respects. For instance, it is increasingly feasible to generate large (50–100 member) ensembles of global climate simulations by a *single* model that allow more precise separation of the simulated greenhouse-warming signal from the noise associated with internal climate variability (Deser *et al* 2014, Mizuta *et al* 2017, Zhang and Delworth 2018).

To date, only a few modeling centers have dedicated their computing resources to such large-ensemble efforts, but with further increases in computer performance it is likely that these projects will become increasingly commonplace. Future computational advances also should make it feasible to represent hydrological processes with increasing realism, and at much finer resolution than is currently possible. It thus seems reasonable to expect that significantly more credible model projections of the impact of greenhouse warming on regional hydroclimates will be forthcoming in the next decade.

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