

LETTER • OPEN ACCESS

Response of electricity sector air pollution emissions to drought conditions in the western United States

To cite this article: Julio E Herrera-Estrada *et al* 2018 *Environ. Res. Lett.* **13** 124032

View the [article online](#) for updates and enhancements.

Environmental Research Letters



LETTER

Response of electricity sector air pollution emissions to drought conditions in the western United States

OPEN ACCESS

RECEIVED

30 August 2018

REVISED

30 October 2018

ACCEPTED FOR PUBLICATION

13 November 2018

PUBLISHED

21 December 2018

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Julio E Herrera-Estrada^{1,2,3} , Noah S Diffenbaugh^{1,4} , Fabian Wagner⁵ , Amy Craft⁶ and Justin Sheffield^{3,7}

¹ Department of Earth System Science, Stanford University, Stanford, CA, United States of America

² Program on Water in the West, Stanford University, Stanford, CA, United States of America

³ Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, United States of America

⁴ Woods Institute for the Environment, Stanford University, Stanford, CA, United States of America

⁵ Air Quality and Greenhouse Gases Program, International Institute for Applied Systems Analysis, Laxenburg, Austria

⁶ Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, United States of America

⁷ Geography and Environment, University of Southampton, Southampton, United Kingdom

E-mail: jehe@stanford.edu

Keywords: drought, water–energy nexus, North America, climate impacts, climate variability, climate change mitigation, emissions

Supplementary material for this article is available [online](#)

Abstract

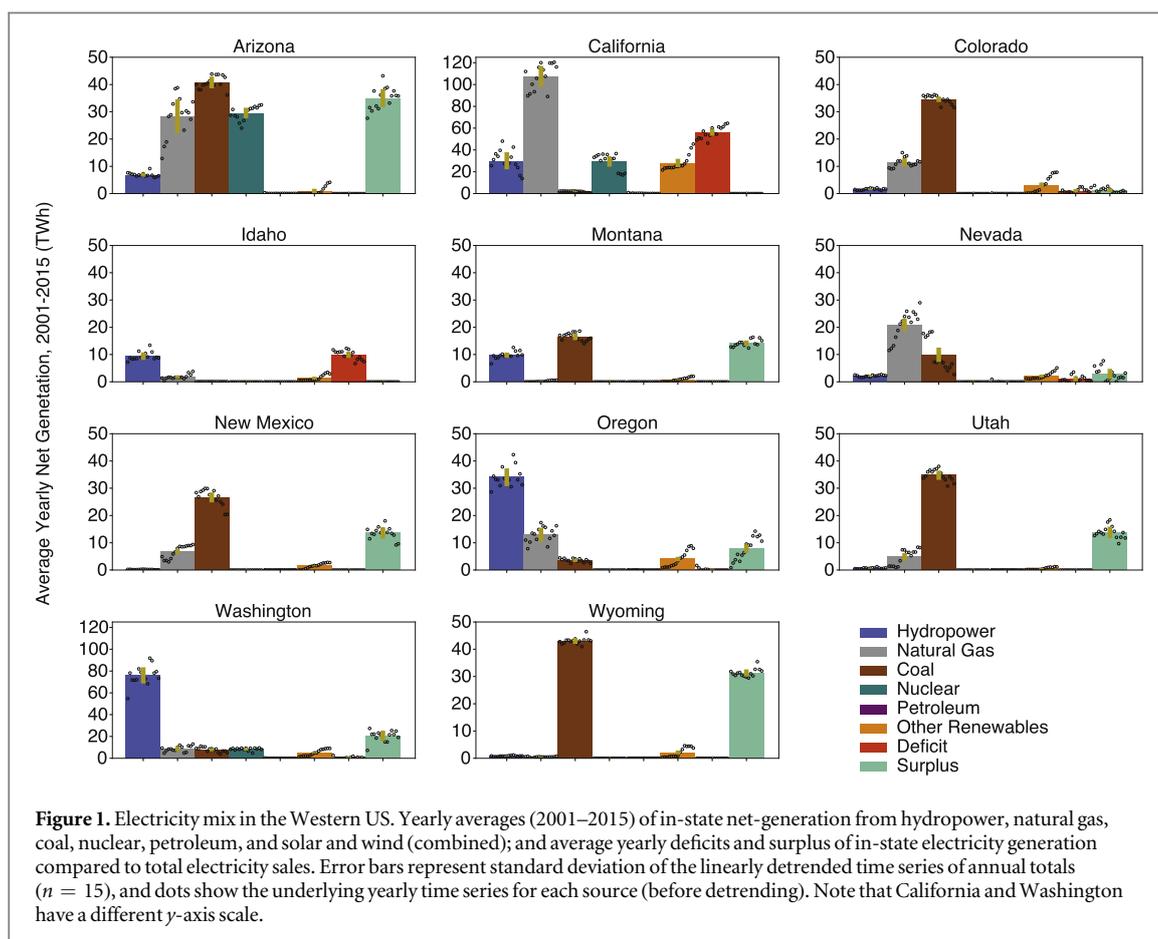
Water is needed for hydroelectric generation and to cool thermoelectric power plants. This dependence on water makes electricity generation vulnerable to droughts. Furthermore, because power sector CO₂ emissions amount to approximately one third of total US emissions, droughts could influence the inter-annual variability of state- and national-scale emissions. However, the magnitude of drought-induced changes in power sector emissions is not well understood, especially in the context of climate mitigation policies. Using multivariate linear regressions, we find that droughts are positively correlated to increases in electricity generation from natural gas in California, Idaho, Oregon, and Washington; and from coal in Colorado, Montana, Oregon, Utah, Washington, and Wyoming. Using a statistical model, we estimate that this shift in generation sources led to total increases in regional emissions of 100 Mt of CO₂, 45 kt of SO₂, and 57 kt of NO_x from 2001 to 2015, most of which originated in California, Oregon, Washington, and Wyoming. The CO₂ emissions induced by droughts in California, Idaho, Oregon, and Washington amounted to 7%–12% of the total CO₂ emissions from their respective power sectors, and the yearly rates were 8%–15% of their respective 2030 yearly targets outlined in the Clean Power Plan (CPP). Although there is uncertainty surrounding the CPP, its targets provide appropriate reference points for climate mitigation goals for the power sector. Given the global importance of hydroelectric and thermoelectric power, our results represent a critical step in quantifying the impact of drought on pollutant emissions from the power sector—and thus on mitigation targets—in other regions of the world.

1. Introduction

Electricity generation requires water resources to drive turbines in hydroelectric dams and to cool thermoelectric power plants that are fueled by nuclear, coal or natural gas. This dependence on water makes the electricity sector vulnerable to droughts (van Vliet *et al* 2012, 2013, 2016a, 2016b, Bartos and Chester 2015, Voisin *et al* 2016, Gleick 2017, Hardin *et al* 2017, Miara *et al* 2017, Eyer and Wichman 2018).

Hydroelectric dams and thermoelectric power plants supply a large fraction of electricity in the western United

States, including 23% and 62%, respectively, in 2015 (EIA 2017). The energy portfolio varies across the region (EIA 2017) (see figure 1), but generally relies on a mix of hydroelectric and thermoelectric power for ‘baseload’ generation (Bartos and Chester 2015). When demand increases, additional coal, natural gas, and petroleum-fueled power plants are dispatched to supply ‘peaking’ generation (Bartos and Chester 2015, Miara *et al* 2017). The order in which power plants are dispatched in the US follows their variable operating costs, with lower-cost plants generally being dispatched first (Sioshansi 2008). Due to their lower operating costs, solar and wind are



generally dispatched together with baseload power plants. While the relative fractions of hydropower to thermoelectric power plants vary from region to region, the dispatch of electricity generation from baseload to peaking power plants in order of variable operating cost is common across the world (IEA 2016a, IEA 2017).

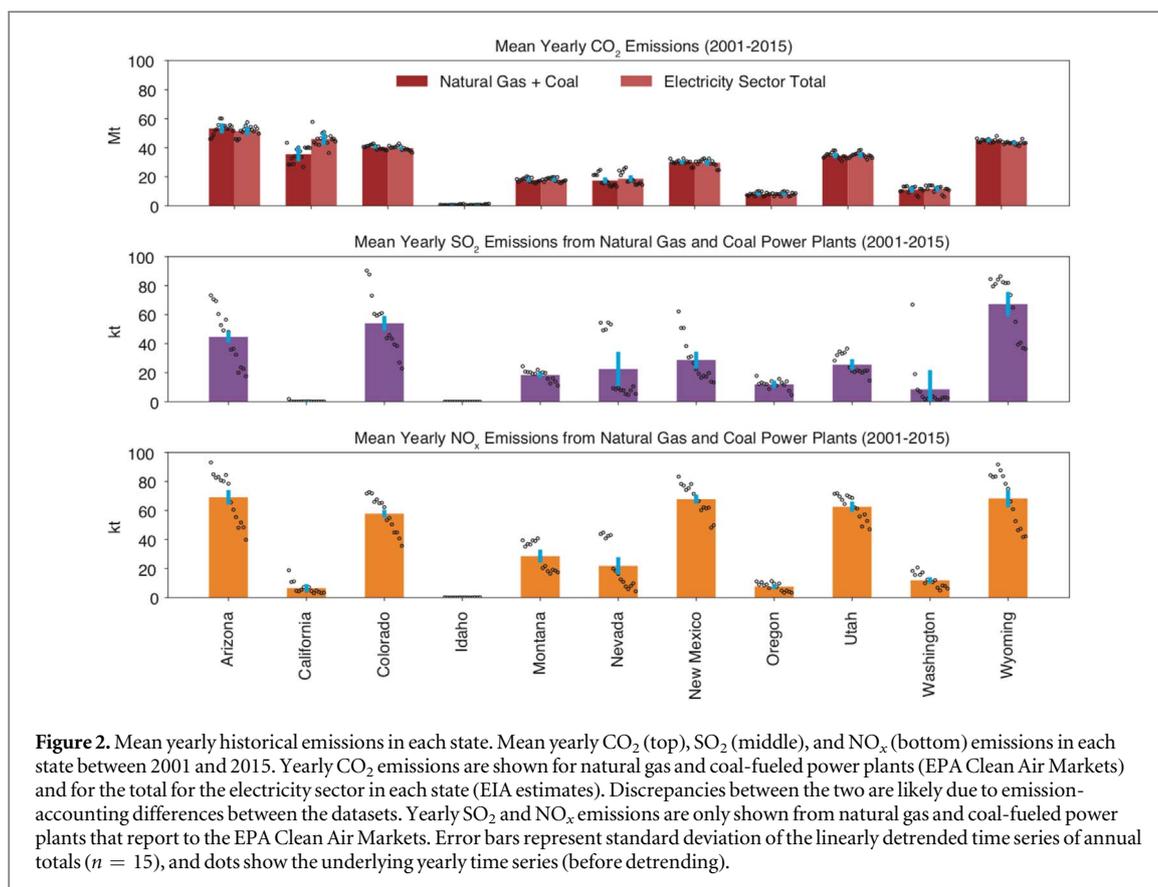
By reducing streamflow, droughts can decrease in-state baseload electricity generation from hydroelectric and thermoelectric sources (Bartos and Chester 2015), thus requiring dispatch of peaking generation plants (Bartos and Chester 2015, Miara *et al* 2017) to prevent brownouts or blackouts. Droughts may also be accompanied by heat waves (e.g. Mazdiyasn and AghaKouchak 2015), requiring dispatch of peaking power plants to meet electricity demand for air conditioning. High air temperatures may lead to warmer streamflow, which can reduce generation capacity from thermoelectric plants via regulatory constraints on the use of streamflow for cooling (van Vliet *et al* 2012, 2016a, 2016b). Depending on the region, cold temperatures during winter may also increase electricity demand for heating.

The increased use of fossil fuel power plants for peak generation induced by droughts may last from months to years, which can lead to significant increases in pollutant emissions from the electricity sector (Gleick 2017, Hardin *et al* 2017, Eyer and Wichman 2018). In addition, decreased in-state electricity

generation due to droughts may increase the need to import electricity from neighboring states (van Vliet *et al* 2013, Voisin *et al* 2016), potentially causing remote increases in pollution.

Past studies have coupled models of surface hydrology, streamflow temperature, and power generation to explore how changes in streamflow and river temperatures affect electricity generation from hydroelectric and thermoelectric plants in current and future climates (van Vliet *et al* 2012, 2013, 2016a, 2016b, Bartos and Chester 2015, Voisin *et al* 2016, Miara *et al* 2017). Other studies used a generation expansion planning model to explore the tradeoffs between water withdrawals, air quality, and electricity generation in the context of planning future generation capacity (Webster *et al* 2013), or applied a plant-scale power generation model over a region to explore the optimal changes in electricity dispatch during droughts (Pacsi *et al* 2013). These modeling approaches tend to focus on either the hydrologic risks faced by individual power plants, or the optimal regional operations of electricity systems in response to water resources constraints.

Recent plant-scale econometric analyses found a positive relationship between water scarcity and emissions from the US electricity sector (Eyer and Wichman 2018), and for the recent California drought (Gleick 2017, Hardin *et al* 2017). Eyer and Wichman (2018) found that in the Western Interconnection,



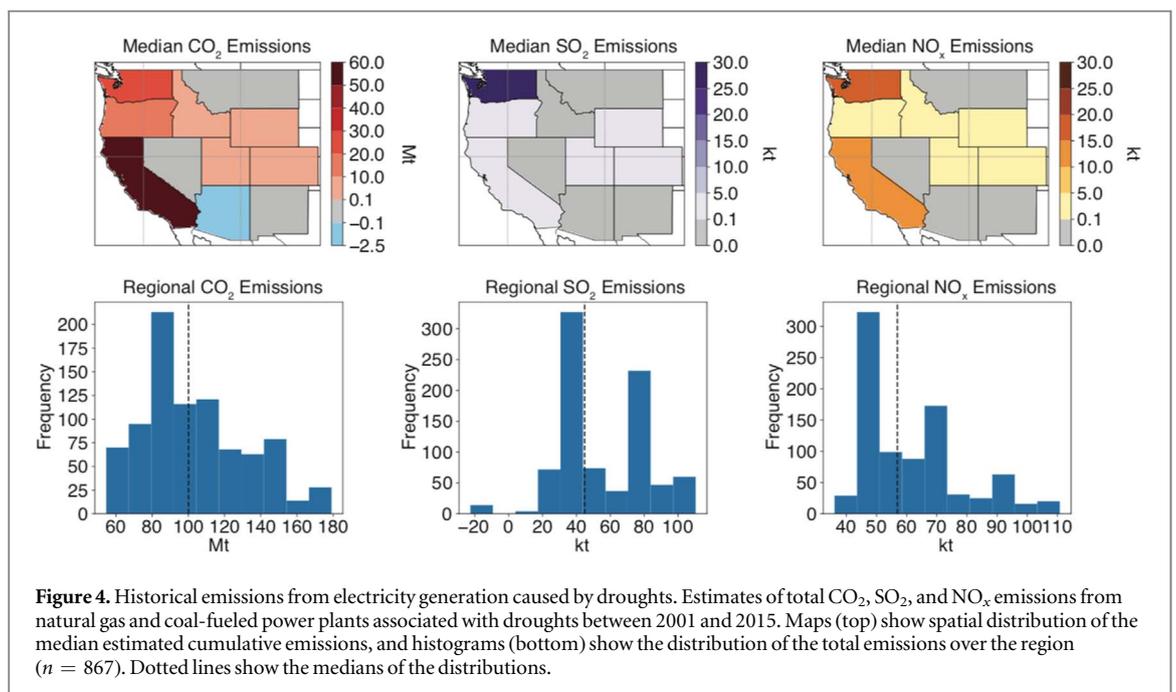
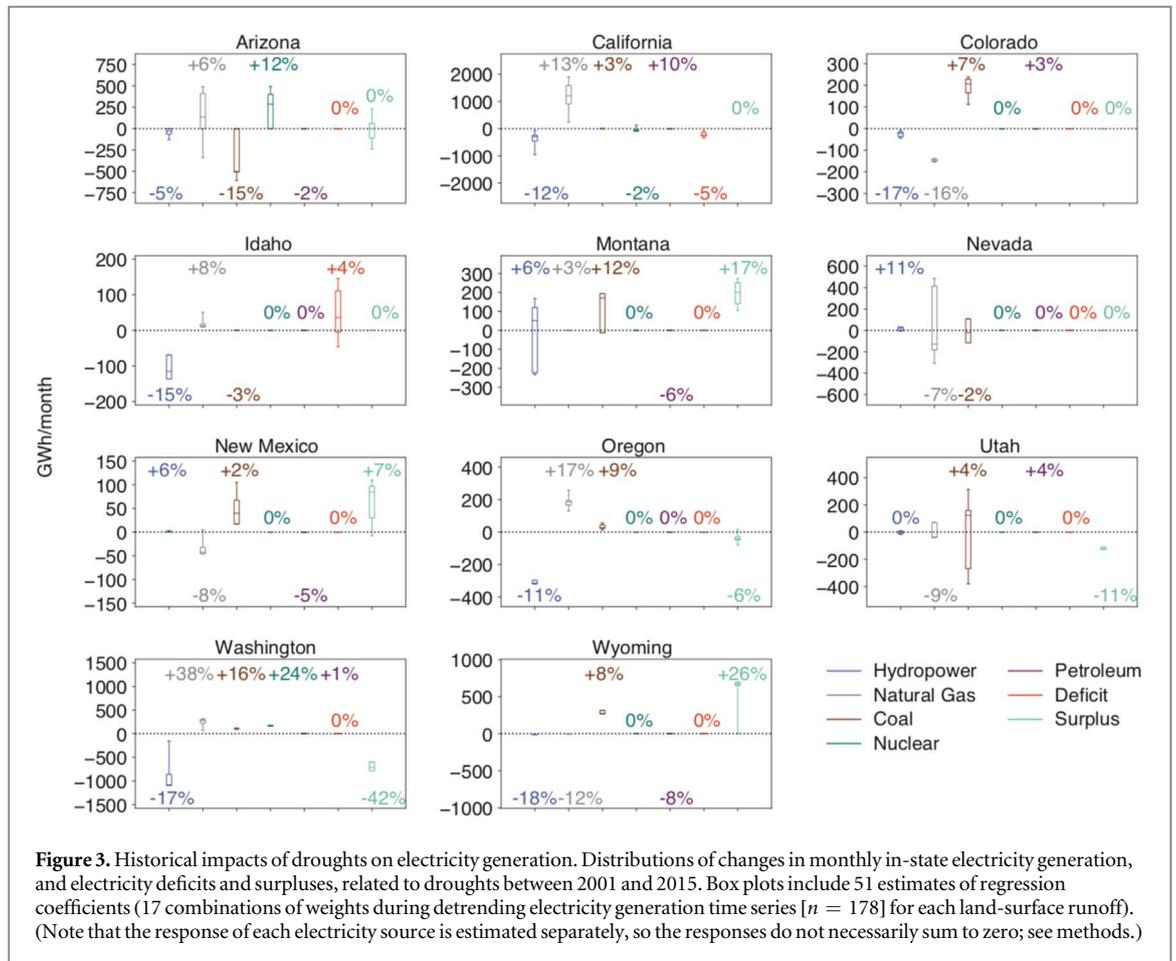
power plants that use once-through cooling and cooling ponds show the strongest relationships with water scarcity, as do power plants that use surface water and municipal water. However, it is still unclear what fraction of historical electricity sector emissions can be attributed to droughts, whether those emissions pose challenges to meeting climate and air quality mitigation targets, and how drought-induced emissions may be affected by future climate change.

Given these questions, we conduct a rigorous statistical analysis of the historical sensitivity of electricity sector emissions to drought. Our approach uses state-wide data on electricity generation and pollutant emissions, combined with a hydrologically-based representation of past droughts. This rigorous characterization of hydrological droughts is critical for adequately quantifying the impacts of climate variability on water availability for electricity generation.

The response of electricity sector emissions to drought is influenced by at least three factors: (1) the frequency, duration, and intensity of droughts; (2) the importance of water-dependent electricity sources in the total electricity portfolio; and (3) the mix of energy sources that replaces the hampered water-dependent power generation. To examine the interaction of these factors, we focus on the western US (figures 1–4), which provides an ideal test case for hydropower regions globally. First, the region relies heavily on hydropower and water-

dependent thermoelectric generation (van Vliet *et al* 2012, 2016a, 2016b, Bartos and Chester 2015, Voisin *et al* 2016, EIA 2017, Mira *et al* 2017, Eyer and Wichman 2018) (figure 1). Second, the electricity mix varies widely across states (figure 1), providing critical variation through which to examine the response to droughts. Third, the states are connected by the Western Interconnection sub-grid, which captures most of these states' electricity trade. Fourth, sub-regional data on electricity generation (EIA 2017) and pollutant emissions (EPA 2017) are available. And fifth, several important droughts have affected the western US in recent years, and it is expected that the region will experience increasing likelihood of droughts due to climate change, in part due to reduced water availability during the spring and summer associated with decreased snowpack (Seager *et al* 2007, 2013, Sheffield and Wood 2008, Rauscher *et al* 2008, Diffenbaugh and Ashfaq 2010, Seager and Vecchi 2010, Ashfaq *et al* 2013, Diffenbaugh *et al* 2008, 2013, 2015, 2017, Maloney *et al* 2014, Wuebbles *et al* 2014, Cook *et al* 2014, 2015, Touma *et al* 2015, Herrera-Estrada and Sheffield 2017, Mankin *et al* 2017, Ting *et al* 2018). This regional drought prevalence provides multiple events through which to measure the response of the electricity sector.

We use a statistical approach to quantify the impacts of droughts directly from observations (in this case from data on electricity generation and power



sector emissions). Our empirical analysis adds to the growing climate econometrics literature, which studies the impacts of short-term climate shocks and long-term climate changes on human activities. Physically-based models often require numerous

assumptions about factors such as water resources allocation, power plant operations and power plant efficiencies, which may introduce important biases. Statistical studies can thus aid the model development process by providing observational benchmarks that

can be used in model parameterization and/or validation.

2. Methods

We use multivariate linear regressions to estimate the impact of drought (characterized by negative runoff anomalies) on electricity generation and pollutant emissions from historical observations between 2001 and 2015. To quantify the relative importance of historical drought-induced emissions, we compare the drought-related CO₂ emissions that we estimate using a statistical model to actual state-level electricity sector totals and policy targets.

2.1. Data

We use monthly data from phase 2 of the North American Land Data Assimilation System (NLDAS-2), which provides data for the contiguous US at 0.125° resolution, from 1979 to the present (Xia *et al* 2012a, 2012b). We use data from three NLDAS-2 land-surface models: VIC (Liang *et al* 1994), Noah (Chen *et al* 1996), and Mosaic (Koster and Suarez 1994). We define drought as periods of negative cumulative runoff anomalies, based on surface runoff and subsurface runoff (i.e. water transport through the soil that recharges streams and reservoirs from underground) (see section 2.2). While all three models show strong correlations with observed streamflow, VIC has been found to represent runoff more accurately than Noah (which overestimates runoff) and Mosaic (which underestimates runoff) (Xia *et al* 2012b). We also calculate population-weighted state averages of total degree day anomalies using NLDAS-2 daily mean air temperatures (see supplementary text 1, figures S1 and S2. These are available online at stacks.iop.org/ERL/13/124032/mmedia for details).

We use monthly state-level electricity generation and sales data from the US Energy Information Agency (EIA; EIA 2017). We calculate electricity deficits and surplus in each state by subtracting the total net in-state electricity generation from total electricity retail sales. We obtain monthly power plant-level measurements of CO₂, SO₂, and NO_x emissions data from the US Environmental Protection Agency (EPA 2017). We aggregate the power plant-level emissions to the state-level by adding the respective emissions from all power plants reporting in each state at each time step (figure 2). We also use yearly CO₂ emissions estimates for the whole electricity sector in each state, provided by the EIA (EIA 2018) (figure 2).

2.2. Characterizing drought

Runoff is the key hydrological variable that determines recharge of rivers and reservoirs, which are the main water sources for the electricity sector in the western US. Thus, calculating a drought index based on runoff data captures hydrological drought dynamics more

accurately than standardized drought indices (e.g. Palmer Drought Severity Index) that may not capture the nonlinear rainfall-runoff relationships accurately due to their oversimplified representation of land-surface fluxes (Liang *et al* 1994, Chen *et al* 1996, Sheffield *et al* 2012, Trenberth *et al* 2014, Xia *et al* 2012a, 2012b).

We add surface and subsurface runoff to calculate total runoff in each month for each NLDAS-2 grid-cell from 1979 to 2017. We create time series of monthly total runoff anomalies by subtracting the respective calendar-month mean from each individual monthly value in the original time series. This anomaly time series thereby quantifies the departure from the long-term mean that occurred in each month. To capture the longer time scales of hydrological droughts (Sheffield and Wood 2011, van Loon 2015), we calculate a running sum of the monthly anomaly time series using accumulation windows of 3, 6, 9, and 12 months (figure S3). We find that the statistical models calibrated using the 12-month window yield lower errors compared to observations, so we use this window throughout the study (see supplementary text 2.4 and 3.2 for the full sensitivity analysis). Finally, we calculate state averages of the cumulative runoff anomalies for each month to match the spatial scale of the electricity generation data (figure S4).

We use a binary drought metric given by equation (1) to calculate a first approximation of the impacts of droughts on electricity generation:

$$d_{i,s} = \begin{cases} 1 & \text{if } \hat{q}_{i,s} \leq -\sigma(\hat{q}_s) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Here, $d_{i,s}$ is the value of the drought metric during month i in state s , $\hat{q}_{i,s}$ is the 12-month cumulative runoff anomaly during month i in state s , and $\sigma(\hat{q}_s)$ is the standard deviation of the 12-month cumulative runoff anomalies in state s calculated using the 1980–2017 time series.

We repeat the analysis using the full time series of 12-month cumulative runoff anomalies (see section 2.3 and supplementary text 2.2). We complete the analyses separately using data from VIC, Noah, and Mosaic to account for hydrological model uncertainty.

2.3. Statistical analysis

The electricity sector evolved across the western US from 2001 to 2015 due to a number of factors, including changes in natural gas prices relative to coal, in availability of solar and wind power, in demand due to population growth, in energy use efficiency, and in policies to reduce greenhouse gas emissions. These trends are evident in the time series of electricity generation and power sector emissions (figures 1 and 2). Because our goal is to quantify the relationship between year-to-year climate variability and power sector variables, we remove these long-term (often nonlinear trends) using piece-wise linear fits. We repeat the detrending exercise 17 times for each time

series to test the sensitivity to the arbitrary choices made in the detrending algorithm (see details of the algorithm in supplementary text 2.1). We propagate this sensitivity analysis through the rest of the calculations, generating distributions of results. Thus, our analyses quantify the drought impacts on the variance of the residuals of the detrended time series.

We calculate multivariate linear regressions between the binary drought metric and the detrended time series of electricity generation (from hydro-power, natural gas, coal, nuclear, and petroleum) and of surpluses and deficits of electricity for each state (see details in supplementary text 2.2). In addition, we repeat the multivariate linear regressions using time series of 12-month cumulative runoff anomalies. The general structure of the regressions is given by equation (2):

$$\log(G_{s,t}) = \beta_0 + \beta_1 Q_{s,t} + \beta_2 T_{s,t} + \lambda_t + u_t, \quad (2)$$

where $G_{s,t}$ is the detrended time series of electricity generation from a given source in state s ; $Q_{s,t}$ is the time series of the binary drought metric or the 12-month cumulative runoff anomalies; and $T_{s,t}$ is the time series of monthly anomalies in population-weighted total degree days in state s . λ_t are controls for each month; β_0 is the regression intercept; β_1 and β_2 are the regression coefficients; and u_t is the stochastic error term. Details of the calculation of absolute changes in generation from the regression coefficients can be found in the supplementary text 2.2.

From these two sets of regressions, we identify groups of states where generation from natural gas is significantly ($p < 0.05$) positively/negatively correlated with drought events (which we call ‘NG+’ and ‘NG−’, respectively). Similarly, we identify groups of states where generation from coal is significantly positively/negatively correlated with droughts (which we call ‘C+’ and ‘C−’, respectively). We detrend the time series of emissions for each state, and pool together the data of states within each of these four groups (NG+, NG−, C+, and C−) to extend the data available to study the impact that droughts of different magnitudes have on CO₂, SO₂, and NO_x emissions. We sort the cumulative runoff anomalies into bins according to their magnitude (figure S4) and calculate multivariate linear regressions for the pooled emissions data similar to equation (2), with additional predictors to determine the effect of droughts of different magnitudes and with controls for the different states that are included (see supplementary Text 2.3 for details).

2.4. Calculating cumulative emissions

We use the results from the pooled, binned regressions described in section 2.3 to build a statistical model that predicts for each state how CO₂, SO₂, and NO_x emissions changed given monthly values of cumulative runoff anomalies and total degree days anomalies from 2001 to 2015 (see supplementary text 3 for details). We repeat this procedure using regression results derived

from VIC, Noah and Mosaic separately, and for the cascading sensitivities from the detrending algorithm, leading to 867 different estimates of drought-induced CO₂, SO₂, and NO_x emissions per state per month from 2001 to 2015. To report the total CO₂, SO₂, and NO_x emissions associated with negative cumulative runoff anomalies (i.e. hydrological droughts) in each state, we first add together the emissions from natural gas- and coal-based generation. We then add the respective monthly estimates for each state to obtain state-level total estimates of CO₂, SO₂, and NO_x emissions throughout these 15 years (2001–2015), and calculate mean yearly rates by dividing these total estimates by 15.

This methodology captures the changes in each state’s emissions caused both by replacing hampered in-state generation capacity and by increasing in-state generation to export electricity to neighboring states that are also affected by a drought (without differentiating between the two). Thus, these relationships apply for the conditions present between 2001 and 2015, including infrastructure, policies, electricity trade patterns, fuel prices, and spatial correlation of droughts.

3. Results

For each state, we calculate the distribution of average drought response of electricity generation from hydro-power, natural gas, coal, petroleum, and nuclear over the 2001–2015 period (figures 3 and S5). We measure the performance of the statistical relationships by calculating the normalized root mean square errors (supplementary text 2.5) shown in figure S6.

Hydropower generation is negatively correlated with drought across the region, led by Wyoming (median change of −18% from non-drought conditions), Washington (−17%), Colorado (−17%), Idaho (−15%), California (−12%), and Oregon (−11%) (figure 3). In contrast, the response of other sources is highly heterogeneous. For example, generation from natural gas exhibits negative correlations with drought in Colorado (−16%) and Wyoming (−12%), but positive correlations in Washington (+38%), Oregon (+17%), California (+13%), and Idaho (+8%). Likewise, generation from coal exhibits negative correlations in Arizona (−15%), and positive correlations in Washington (+16%), Montana (+12%), Oregon (+9%), Wyoming (+8%), and Colorado (+8%). Note that these are percentage departures from mean generation, so in California a 13% increase in generation from natural gas translates to a change of 1204 GWh/month, while in Washington a 38% increase translates to 274 GWh/month (figure 3). The heterogeneity of the drought response largely reflects the average state-level energy mix (figure 1), with negative correlations suggesting sources hampered by drought and positive correlations suggesting sources used for replacement generation.

Table 1. Historical emissions from electricity generation caused by droughts in each state. Median estimates ($n = 867$) of total CO₂, SO₂, and NO_x emissions from natural gas and coal-fueled power plants induced by droughts in each state between 2001 and 2015. Right columns for each pollutant represent the values as a percentage of the total historical emissions from the power sector (2001–2015) (figure 2). Median regional values are calculated from the distributions of regional totals (not the sum of the medians for each state). CO₂ percentages are relative to totals from the electricity sector. SO₂ and NO_x percentages are relative to total emissions from natural gas and coal-fueled power plants that report to the EPA Clean Air Markets. The full distributions are shown in figure S12. Tons were rounded to the nearest ten.

State	CO ₂		SO ₂		NO _x	
	Value (Mt)	Percentage of total	Value (tons)	Percentage of total	Value (tons)	Percentage of total
Arizona	−2.1	−0.3%	0	0.0%	0	0.0%
California	51.3	7.4%	680	13.4%	14 210	14.6%
Colorado	1.2	0.2%	4820	0.6%	5000	0.6%
Idaho	1.0	9.0%	20	37.1%	220	11.2%
Montana	0.0	0.0%	0	0.0%	0	0.0%
Nevada	0.0	0.0%	0	0.0%	0	0.0%
New Mexico	0.0	0.0%	0	0.0%	0	0.0%
Oregon	13.5	11.0%	160	0.1%	3180	2.8%
Utah	0.8	0.1%	4970	1.3%	1990	0.2%
Washington	21.8	12.4%	27 240	21.3%	18 310	10.3%
Wyoming	6.9	1.1%	3420	0.3%	4110	0.4%
Regional	100.1	2.2%	44 840	1.1%	56 910	0.9%

The Western Interconnection also enables electricity to be traded within the region. The in-state generation deficit exhibits positive correlations in Idaho (+4%), suggesting increasing need for imports. Conversely, the in-state generation surplus exhibits negative correlations in Washington (−42%), Utah (−11%), and Oregon (−6%), suggesting a reduced ability to export; and positive correlations in Wyoming (+26%) and Montana (+17%). The pattern of drought response suggests that generation from coal increases in Wyoming and Montana in order to export electricity to surrounding states that experience drought-induced declines in generation.

We calculate multivariate linear regressions to estimate CO₂, SO₂, and NO_x emissions linked to drought-induced changes in generation from natural gas and coal in states that show similar responses (NG+, NG−, C+, C− figures S7–S11). We find that the largest increases in CO₂ emissions occur in California (median estimate of 51.3 Mt, total between 2001–2015), Washington (21.8 Mt), Oregon (13.5 Mt) and Wyoming (6.9 Mt) (figure 4 and table 1). Emissions in Washington amounted to 12.4% of the total power sector CO₂ emissions from the state, compared with 11.0% for Oregon, 7.4% for California, and 1.1% for Wyoming (which has relatively high state-level total power sector emissions; figure 2). On the other hand, the power sector in Idaho emits relatively little CO₂, so although estimated drought-induced emissions for Idaho are only 1.0 Mt, these amount to 9.0% of its total power sector emissions. While the total emissions are key for climate change mitigation globally, the relative amounts for each state are important when developing state-specific emissions-reduction targets.

Arizona shows a negative relationship between coal-fueled generation and droughts, and a positive relationship between natural gas-fueled generation and droughts (figures 3, S5, and S7). The combination of these two effects results in ‘negative’ CO₂ emissions

in our statistical model, but no changes in SO₂ or NO_x emissions. However, it should be noted that there were few negative 12-month cumulative runoff anomalies in Arizona between 2001 and 2015 (figure S4).

The largest estimated increases in SO₂ occurred in Washington (27.2 kt), Utah (5.0 kt), Colorado (4.8 kt), and Wyoming (3.4 kt) (table 1). Washington’s emissions amounted to 21.3% of the state’s total power sector SO₂ emissions. For NO_x, the largest estimated increases in emissions occurred in Washington (18.3 kt), California (14.2 kt), Colorado (5.0 kt), Wyoming (4.1 kt), Oregon (3.2 kt), and Utah (2.0 kt). Washington’s and California’s estimated NO_x emissions amounted to 10.3% and 14.6% of state-level NO_x emission totals, respectively.

The spatial distribution of changes generally resembles the underlying electricity mix (figure 1), with states that either rely heavily on hydropower (e.g. Washington, California, and Oregon) or coal-fueled generation (e.g. Wyoming, Utah, and Colorado) producing higher emissions in response to drought. The size of California’s electricity sector represents a unique case. For example, although hydropower supplies a smaller fraction of electricity in California than in Oregon (figure 1), and although California’s hampered hydropower is replaced by a less carbon-intensive alternative (natural gas) than Oregon’s (coal and natural gas) (figure 3), California’s large total electricity demand (figure 1) means that California experiences greater increases in total CO₂ emissions during droughts (table 1).

We estimate the total 2001–2015 drought-induced emissions over the western US to be 100.1 Mt of CO₂, 44.8 kt of SO₂, and 56.9 kt of NO_x. The annual-mean increase in regional CO₂ (6.7 Mt of CO₂/year) is equivalent to the emissions of ~1.45 million vehicles/year (assuming 4.6 metric tons of emissions per vehicle/year, EPA 2018), or ~5.7% of the automobiles

Table 2. Drought-related CO₂ emissions relative to climate mitigation targets. Median estimates of yearly CO₂ emissions in each state as percentages of total historic emissions from the electricity sector in each state and of state-specific yearly emission targets (see supplementary table 1 for target values). Targets 1 and 2 refer to CO₂ emission targets proposed by state governments across sectors. States without individual targets are shown as missing values.

State	Percentage of historical totals (2001–2015)	Percentage of Clean Power Plan target (2030)	Percentage of target 1 (2020–2025)	Percentage of target 2 (2030–2050)
Arizona	−0.3%	−0.5%	−0.2%	—
California	7.4%	7.8%	0.8%	1.3%
Colorado ^a	0.2%	0.3%	0.3%	0.3%
Idaho	9.0%	4.6%	—	—
Montana	0.0%	0.0%	—	—
Nevada	0.0%	0.0%	—	—
New Mexico	0.0%	0.0%	0.0%	0.0%
Oregon	11.0%	12.2%	1.8%	6.5%
Utah	0.1%	0.2%	—	—
Washington	12.4%	15.0%	1.6%	3.3%
Wyoming	1.1%	1.6%	—	—

^a Colorado targets are specific for the electricity sector.

registered in California as of 2016 (California DMV 2017). Further, we estimate that the recent California drought (2011–2015 in our analysis) led to an additional 22.6 Mt of CO₂, 0.3 kt of SO₂, and 6.2 kt of NO_x, generally consistent with previous estimates (Gleick 2017, Hardin *et al* 2017). (See figure S12 for the distributions of emissions per state, figure S13 for details on the California drought, and figure S14 for the sensitivity of regional emissions to the window of the cumulative runoff anomalies.)

These drought-induced emissions are large enough to pose challenges to western states' progress towards their CO₂ emissions targets. Table 2 shows annual-mean (2001–2015), state-level drought-induced CO₂ emissions as percentages of (1) the states' total emissions from the electricity sector between 2001–2015, (2) targets of annual CO₂ rates established by the Clean Power Plan (CPP) (EPA 2015), and (3) state-specific targets of yearly CO₂ rates (supplementary table 1). While there is uncertainty regarding the implementation of the CPP targets, they provide policy benchmarks for electricity sector emissions. We find that drought-induced emissions can account for a significant portion of electricity sector emissions and related targets. For example, mean annual drought-induced emissions between 2001 and 2015 represent 15.0% of the 2030 CPP target for Washington, 12.2% for Oregon, and 7.8% for California. Thus, our results highlight the importance of the carbon intensity of the electricity sources that are used to replace hampered hydroelectric and thermoelectric generation during droughts.

4. Discussion and conclusions

We derive robust statistical relationships between runoff anomalies and state-level power sector emissions of CO₂, SO₂, and NO_x. We characterize drought using runoff because it is an appropriate hydrological variable to study drought impacts on the power sector at the

state-level, and NLDAS-2 models capture its behavior with high accuracy (Xia *et al* 2012b). Our results suggest that, between 2001 and 2015, power sector emissions attributable to droughts reached ~10% of the average total annual power sector emissions in California, Idaho, Oregon, and Washington.

Our results are in general agreement with recent analyses using plant-level data (Eyer and Wichman 2018), which found that natural gas is often used to replace hampered generation during droughts. However, Eyer and Wichman (2018) did not find strong relationships between generation from coal and water scarcity in the Western Interconnection. They also did not find statistically significant increases in CO₂ and NO_x in the Western Interconnection, except when pooling data from across the country. We believe that this difference arises from the structure of our regressions, which allows for flexibility in capturing the response across the highly heterogeneous energy mix within the Western Interconnection. By carrying out the analysis over each state individually, we identify both positive and negative state-level correlations between coal generation and drought, suggesting that the impact of drought on coal generation varies widely depending on the state. Creating separate statistical models for groups of states that show similar behaviors allows us to capture the heterogeneous drought response across the region.

Climate change could alter the pattern of drought frequency and severity in future decades, particularly during the spring and summer due to reduced snowpack (Seager *et al* 2007, 2013, Sheffield and Wood 2008, Rauscher *et al* 2008, Diffenbaugh and Ashfaq 2010, Seager and Vecchi 2010, Ashfaq *et al* 2013, Diffenbaugh *et al* 2008, 2013, 2015, 2017, Maloney *et al* 2014, Wuebbles *et al* 2014, Cook *et al* 2014, 2015, Touma *et al* 2015, Herrera-Estrada and Sheffield 2017, Mankin *et al* 2017, Ting *et al* 2018). Even if aggressive global mitigation efforts consistent with the U.N. Paris Agreement (UNFCCC 2015) are achieved, regional drought-induced emissions are likely to continue at

their historical levels (absent other interventions such as investments in renewable technology and thermo-electric power plants with more efficient cooling systems and emissions controls).

California, Oregon, and Washington have established aggressive emissions-reduction targets through legislation (e.g. California ARB 2017), so even if the CPP is not implemented, emissions from the power sectors in these states may generally decrease as they strive to meet their state-level targets. However, our results raise the importance of considering drought-induced emissions from the power sector when developing mitigation policies. In addition to the first-order priority of replacing baseload generation with low-emission sources, meeting state-level goals may also require replacing peaking-plants with low-emission sources. In California, generation from renewables is increasing, but nuclear fission power plants (a low-emissions energy source) are being retired (e.g. Davis and Hausman 2016). Unless enough renewables are brought online to replace the retired nuclear power, California could see a relative increase in drought-induced emissions as more natural gas power plants are brought online more frequently. Alternatively, California may drive up emissions in surrounding states if it increasingly relies on electricity imports from states that lack strong climate mitigation policies.

A recent report by the US Department of Energy outlined a roadmap to increase hydropower capacity by 50% by 2050, mainly by upgrading existing facilities, adding power generation capability to non-powered dams, and increasing pumped-storage (DOE 2016). Following this expansion raises the importance of considering the vulnerability of electricity generation to climate variability. Moreover, the issue of drought-induced emissions is of global importance. Hydropower accounts for 16% of the world's electricity (including as high as 56% in Latin America; IEA 2016a, 2017), with an expected increase in worldwide generation of 47%–70% by 2040 from 2016 levels (IEA 2016b). In addition, thermoelectric power plants are responsible for 70% of the world's electricity (IEA 2016a, 2016b), of which fossil fuel power plants account for 58% of all energy-related water withdrawals (IEA 2016b) and 25% of all greenhouse gas emissions globally (IPCC 2014). Our study reveals the potential significance of drought-related emissions from the power sector, and highlights their importance for achieving emissions targets. In addition, the prospect of future increases in droughts globally (e.g. Sheffield and Wood 2008, 2011, Diffenbaugh and Giorgi 2012, Diffenbaugh *et al* 2013, Cook *et al* 2014, 2018, Trenberth *et al* 2014, Touma *et al* 2015, Wanders and Van Lanen 2015, Wanders and Wada 2015, Wanders *et al* 2015, van Vliet *et al* 2016a, 2016b, Naumann *et al* 2018, Berg and Sheffield 2018) raises the question of whether global-scale drought-induced emissions could be large enough to significantly impact global climate forcing, and hence drive further changes in regional climate and associated drought risk.

Acknowledgments

We thank two anonymous reviewers for insightful and constructive comments. We thank Niklas Engbom for his insights on econometrics, as well as Michael Oppenheimer; the Science, Technology, and Environmental Policy Program and the Terrestrial Hydrology Research Group at Princeton University; and the Climate and Earth System Dynamics Group at Stanford University for their feedback. This research was funded by the NASA Earth and Space Science Fellowship award NNX14AL08H, NOAA award NA14OAR4310218, the Department of Energy, and Stanford University.

ORCID iDs

Julio E Herrera-Estrada  <https://orcid.org/0000-0002-7767-2636>

Noah S Diffenbaugh  <https://orcid.org/0000-0002-8856-4964>

Fabian Wagner  <https://orcid.org/0000-0003-3429-2374>

Justin Sheffield  <https://orcid.org/0000-0003-2400-0630>

References

- Ashfaq M, Ghosh G, Kao S-C, Bowling L C, Mote P, Touma D, Rauscher S A and Diffenbaugh N 2013 Near-term acceleration of hydroclimatic changes in the western US *J. Geophys. Res. Atmos.* **118** 10 676–93
- Bartos M D and Chester M V 2015 Impacts of climate change on electric power supply in the Western United States *Nat. Clim. Change* **5** 748–52
- Berg A and Sheffield J 2018 Climate change and drought: the soil moisture perspective *Curr. Clim. Change Rep.* **4** 180–91
- California ARB 2017 California's 2017 Climate Change Scoping Plan (www.arb.ca.gov/cc/scopingplan/scoping_plan_2017.pdf)
- California DMV 2017 Statistics for Publication January Through December 2016 (DMV Forecasting Unit (916) 657-8008) (www.dmv.ca.gov/portal/wcm/connect/5aa16cd3-39a5-402f-9453-0d353706cc9a/official.pdf?MOD=AJPERES)
- Chen F, Mitchell K, Schaake J, Xue Y, Pan H-L, Koren V, Duan Q Y, Ek M and Betts A 1996 Modeling of land surface evaporation by four schemes and comparison with FIFE observations *J. Geophys. Res.* **101** 7251–68
- Cook B I, Ault T R and Smerdon J E 2015 Unprecedented 21st century drought risk in the American Southwest and Central Plains *Sci. Adv.* **1** e1400082
- Cook B I, Mankin J M and Anchukaitis K J 2018 Climate change and drought: from past to future *Curr. Clim. Change Rep.* **4** 164–79
- Cook B I, Smerdon J E, Seager R and Coats S 2014 Global warming and 21st century drying *Clim. Dyn.* **43** 2607–27
- Davis L and Hausman C 2016 Market impacts of a nuclear power plant closure *Am. Econ. J.: Appl. Econ.* **8** 92–122
- Diffenbaugh N S and Ashfaq M 2010 Intensification of hot extremes in the United States *Geophys. Res. Lett.* **37** L15701
- Diffenbaugh N S and Giorgi F 2012 Climate change hotspots in the CMIP5 global climate model ensemble *Clim. Change* **114** 813–22
- Diffenbaugh N S, Giorgi F and Pal J S 2008 Climate change hotspots in the United States *Geophys. Res. Lett.* **35** L16709
- Diffenbaugh N S, Scherer M and Ashfaq M 2013 Response of snow-dependent hydrologic extremes to continued global warming *Nat. Clim. Change* **3** 379–84

- Diffenbaugh N S, Swain D L and Touma D 2015 Anthropogenic warming has increased drought risk in California *Proc. Natl Acad. Sci. USA* **112** 3931–6
- Diffenbaugh N S *et al* 2017 Quantifying the influence of global warming on unprecedented extreme climate events *Proc. Natl Acad. Sci. USA* **114** 4881–6
- DOE 2016 Hydropower Vision (GO-102016-4869, 396pp) (www.energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf)
- EIA 2017 *Electricity Generation Dataset* Form EIA-923 (www.eia.gov/electricity/data/eia923)
- EIA 2018 Electricity Emissions by State (2001–2015) (www.eia.gov/environment/emissions/state)
- EPA 2018 Greenhouse Gas Emissions from a Typical Passenger Vehicle
- EPA 2015 Carbon pollution emission guidelines for existing stationary sources: electric utility generating units *Fed. Register* **80** 64661–964
- EPA 2017 Air Markets Program Data (<https://ampd.epa.gov/ampd>)
- Eyer J and Wichman C J 2018 Does water scarcity shift the electricity generation mix toward fossil fuels? Empirical evidence from the United States *J. Environ. Econ. Manage.* **87** 224–41
- Gleick P 2017 *Impacts of California's Five-Year (2012–2016) Drought on Hydroelectricity Generation* (London: The Pacific Institute)
- Hardin E, AghaKouchak A, Qomi M J A, Madani K, Tarroja B, Zhou Y, Yang T and Samuelsen S 2017 California drought increases CO₂ footprint of energy *Sustain. Cities Soc.* **28** 450–2
- Herrera-Estrada J E and Sheffield J 2017 Uncertainties in future projections of summer droughts and heat waves over the contiguous United States *J. Clim.* **30** 6225–46
- IEA 2016a *World Energy Outlook 2016* (Paris: IEA)
- IEA 2016b *Water Energy Nexus (Excerpt from the)* (Paris: IEA)
- IEA 2017 *World Energy Outlook 2017* (Paris: IEA)
- IPCC 2014 Summary for policymakers *Climate Change, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer (Cambridge: Cambridge University Press)
- Koster R and Suarez M 1994 The components of the SVAT scheme and their effects on a GCM hydrological cycle *Adv. Water Resour.* **17** 61–78
- Liang X, Lettenmaier D P, Wood E F and Burges S J 1994 A simple hydrologically based model of land surface water and energy fluxes for general circulation models *J. Geophys. Res.* **99** 14415–28
- Maloney E D *et al* 2014 North American climate in CMIP5 experiments: III. Assessment of twenty-first-century projections *J. Clim.* **27** 2230–70
- Mankin J S, Smerdon J E, Cook B I, Williams A P and Seager R 2017 The curious case of projected twenty-first-century drying but greening in the American West *J. Clim.* **30** 8689–710
- Mazdiyasi O and AghaKouchak A 2015 Substantial increase in concurrent droughts and heat waves in the United States *Proc. Natl Acad. Sci.* **112** 11484–9
- Miara A, Macknick J E, Vörösmarty C J, Tidwell V C, Newmark R and Fekete B 2017 Climate and water resource change impacts and adaptation potential for US power supply *Nat. Clim. Change* **7** 793–8
- Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts R A, Carrao H, Spinoni J, Vogt J and Feyen L 2018 Global changes in drought conditions under different levels of warming *Geophys. Res. Lett.* **45** 3285–96
- Pacsi A P, Alhajeri N S, Webster M D, Webber M E and Allen D T 2013 Changing the spatial location of electricity generation to increase water availability in areas with drought: a feasibility study and quantification of air quality impacts in Texas *Environ. Res. Lett.* **8** 35029
- Rauscher S A, Pal J S, Diffenbaugh N S and Benedetti M M 2008 Future changes in snowmelt-driven runoff timing over the western US *Geophys. Res. Lett.* **35** L16703
- Seager R *et al* 2007 Model projections of an imminent transition to a more arid climate in Southwestern North America *Science* **316** 1181–4
- Seager R, Ting M, Li C, Naik N, Cook B, Nakamura J and Liu H 2013 Projections of declining surface-water availability for the southwestern United States *Nat. Clim. Change* **3** 482–6
- Seager R and Vecchi G A 2010 Greenhouse warming and the 21st century hydroclimate of southwestern North America *Proc. Natl Acad. Sci.* **107** 21277–82
- Sheffield J and Wood E F 2008 Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations *Clim. Dyn.* **31** 79–105
- Sheffield J and Wood E F 2011 *Drought: Past Problems and Future Scenarios* (New York: Routledge)
- Sheffield J, Wood E F and Roderick M L 2012 Little change in global drought over the past 60 years *Nature* **491** 435–8
- Sioshansi F P 2008 *Competitive Electricity Markets: Design, Implementation, Performance* (Amsterdam: Elsevier)
- Ting M, Seager R, Li C, Liu H and Henderson N 2018 Mechanism of future spring drying in the Southwestern United States in CMIP5 models *J. Clim.* **31** 4265–79
- Touma D, Ashfaq M, Nayak M A, Kao S-C and Diffenbaugh N S 2015 A multi-model and multi-index evaluation of drought characteristics in the 21st century *J. Hydrol.* **526** 196–207
- Trenberth K E, Dai A, Van Der Schrier G, Jones P D, Barichivich J, Briffa K R and Sheffield J 2014 Global warming and changes in drought *Nat. Clim. Change* **4** 17–22
- UNFCCC 2015 Paris Agreement (Paris, 12 December 2015) (https://treaties.un.org/doc/Treaties/2016/02/20160215%2006-03%20PM/Ch_XXVII-7-d.pdf)
- van Loon A F 2015 Hydrological drought explained *WIREs Water* **2** 359–92
- van Vliet M T H, Sheffield J, Wiberg D and Wood E F 2016a Impacts of recent drought and warm years on water resources and electricity supply worldwide *Environ. Res. Lett.* **11** 124021
- van Vliet M T H, van Wiberg D, Leduc S and Riahi K 2016b Power-generation system vulnerability and adaptation to changes in climate and water resources *Nat. Clim. Change* **6** 375–80
- van Vliet M T H, Vögele S and Rübberke D 2013 Water constraints on European power supply under climate change: impacts on electricity prices *Environ. Res. Lett.* **8** 35010
- van Vliet M T H, Yearsley J R, Ludwig F, Vögele S, Lettenmaier D P and Kabat P 2012 Vulnerability of US and European electricity supply to climate change *Nat. Clim. Change* **2** 676–81
- Voisin N, Kintner-Meyer M, Skaggs R, Nguyen T, Wu D, Dirks J, Xie Y and Hejazi M 2016 Vulnerability of the US western electric grid to hydro-climatological conditions: how bad can it get? *Energy* **115** 1–12
- Wanders N and Van Lanen H A J 2015 Future discharge drought across climate regions around the world modelled with a synthetic hydrological modelling approach forced by three general circulation models *Nat. Hazards Earth Syst. Sci.* **15** 487–504
- Wanders N and Wada Y 2015 Human and climate impacts on the 21st century hydrological drought *J. Hydrol.* **526** 208–20
- Wanders N, Wada Y and Van Lanen H A 2015 Global hydrological droughts in the 21st century under a changing hydrological regime *Earth Syst. Dyn.* **6** 1–15
- Webster M, Donohoo P and Palmintier B 2013 Water-CO₂ trade-offs in electricity generation planning *Nat. Clim. Change* **3** 1029–32
- Wuebbles D *et al* 2014 CMIP5 climate model analyses: Climate extremes in the United States *Bull. Am. Meteorol. Soc.* **95** 571–83
- Xia Y *et al* 2012a Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): I. Intercomparison and application of model products *J. Geophys. Res.* **117** D03109
- Xia Y *et al* 2012b Continental-scale water and energy flux analysis and validation for North American Land Data Assimilation System project phase 2 (NLDAS-2): 2. Validation of model-simulated streamflow *J. Geophys. Res.* **117** D03110