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LETTER

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

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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 CO_2 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 CO_2, 45 kt of SO_2, and 57 kt of NO_x from 2001 to 2015, most of which originated in California, Oregon, Washington, and Wyoming. The CO_2 emissions induced by droughts in California, Idaho, Oregon, and Washington amounted to 7%–12% of the total CO_2 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

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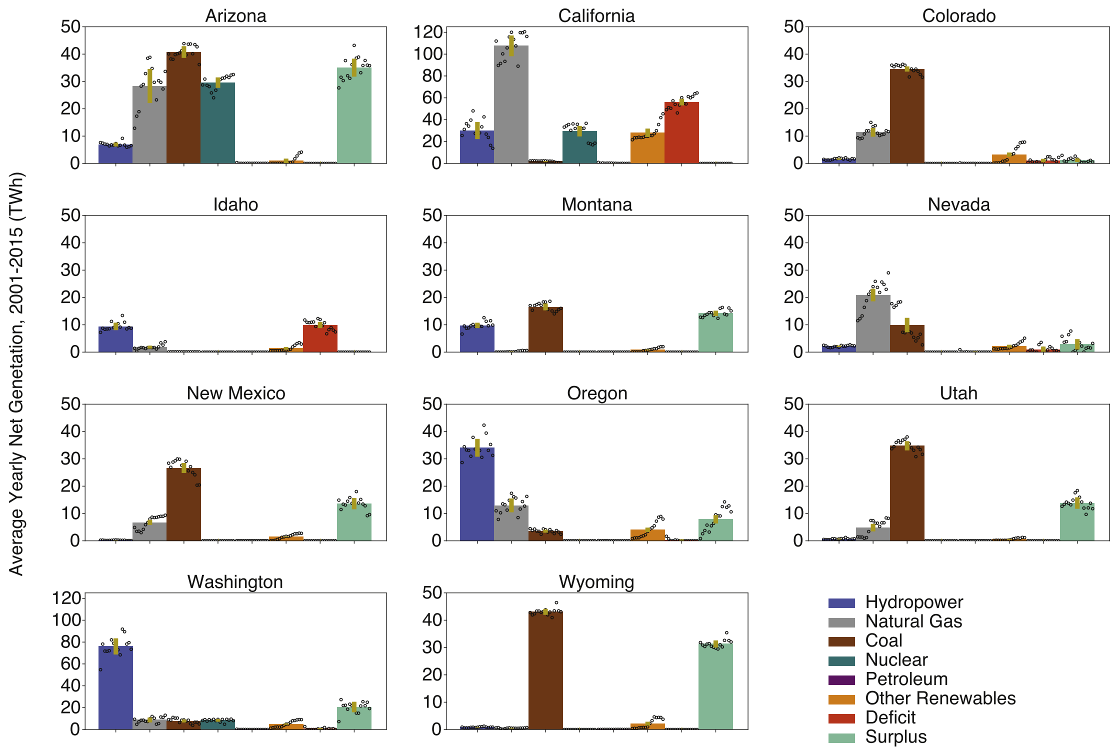

Figure 1. Electricity mix in the Western US. Yearly averages (2001–2015) of in-state net-generation from hydropower, natural gas, coal, nuclear, petroleum, and solar and wind (combined); and average yearly deficits and surplus of in-state electricity generation compared to total electricity sales. Error bars represent standard deviation of the linearly detrended time series of annual totals ($n = 15$), and dots show the underlying yearly time series for each source (before detrending). Note that California and Washington have a different y-axis scale.

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. Mazdiyasni 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,

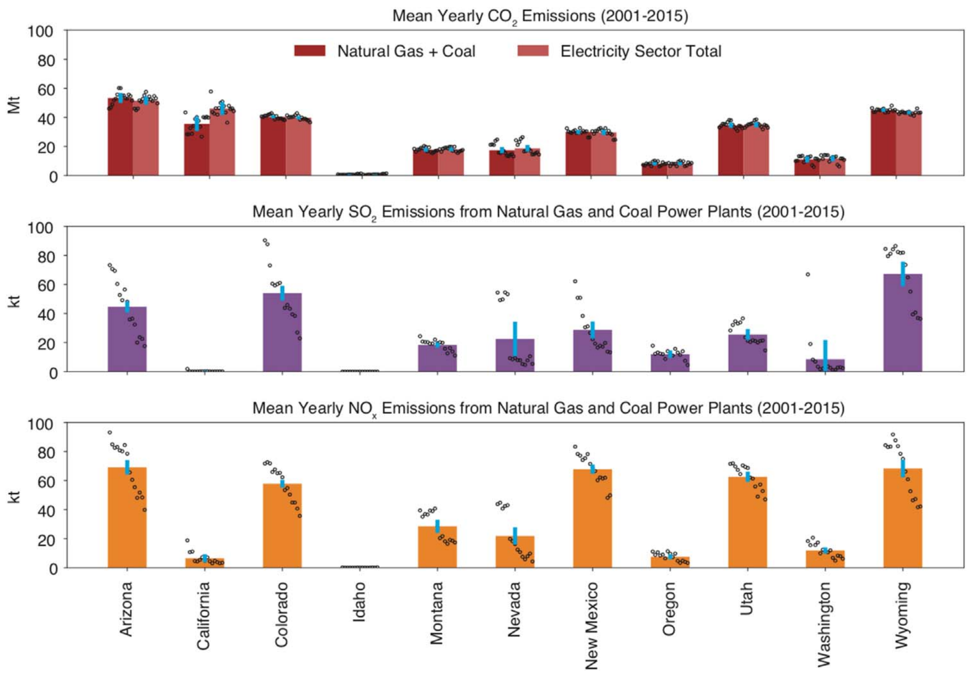

Figure 2. Mean yearly historical emissions in each state. Mean yearly CO_2 (top), SO_2 (middle), and NO_x (bottom) emissions in each state between 2001 and 2015. Yearly CO_2 emissions are shown for natural gas and coal-fueled power plants (EPA Clean Air Markets) and for the total for the electricity sector in each state (EIA estimates). Discrepancies between the two are likely due to emission-accounting differences between the datasets. Yearly SO_2 and NO_x emissions are only shown from natural gas and coal-fueled power plants that report to the EPA Clean Air Markets. Error bars represent standard deviation of the linearly detrended time series of annual totals ($n = 15$), and dots show the underlying yearly time series (before detrending).

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

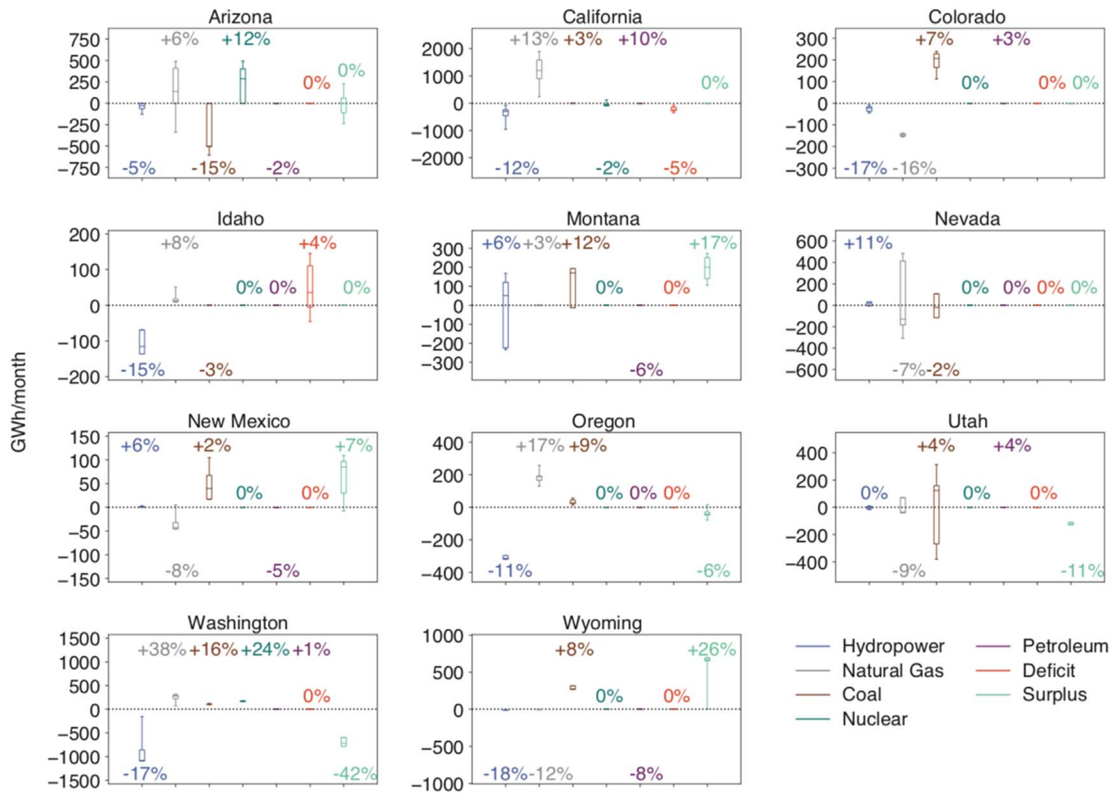

Figure 3. Historical impacts of droughts on electricity generation. Distributions of changes in monthly in-state electricity generation, and electricity deficits and surpluses, related to droughts between 2001 and 2015. Box plots include 51 estimates of regression coefficients (17 combinations of weights during detrending electricity generation time series [$n = 178$] for each land-surface runoff). (Note that the response of each electricity source is estimated separately, so the responses do not necessarily sum to zero; see methods.)

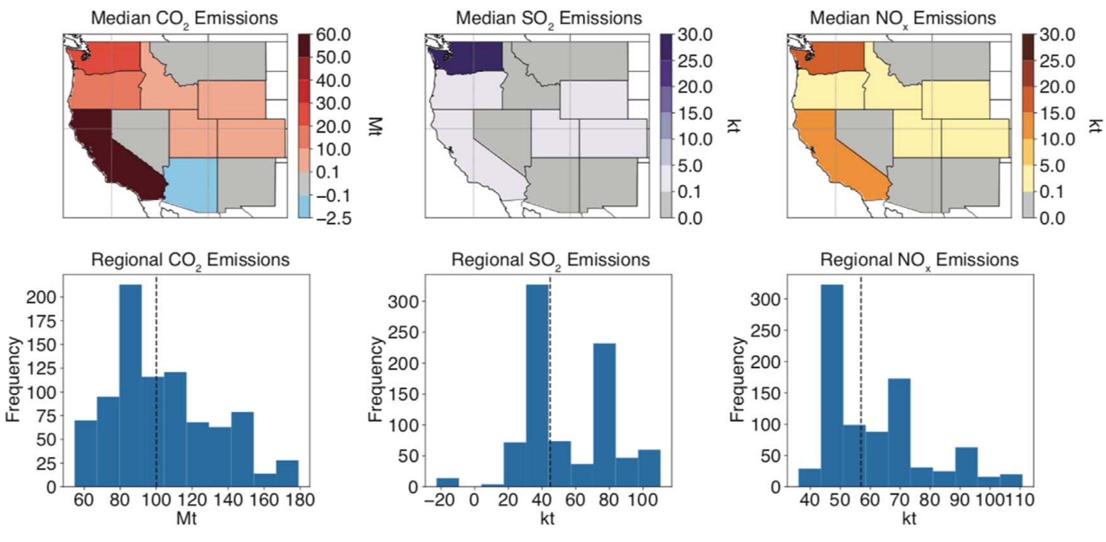

Figure 4. Historical emissions from electricity generation caused by droughts. Estimates of total CO_2, SO_2, and NO_x emissions from natural gas and coal-fueled power plants associated with droughts between 2001 and 2015. Maps (top) show spatial distribution of the median estimated cumulative emissions, and histograms (bottom) show the distribution of the total emissions over the region ($n = 867$). Dotted lines show the medians of the distributions.

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 CO_2 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 CO_2, SO_2, 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 CO_2 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:

$$d_{i,s} = \begin{cases} 1 & \text{if } \hat{q}_{i,s} \leqslant -\sigma(\widehat{q_s}) \\ 0 & \text{otherwise} \end{cases}. \tag{1}$$

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 $\sigma(\widehat{q_s})$ 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 hydropower, 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 CO_2, SO_2, 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 CO_2, SO_2, 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 CO_2, SO_2, and NO_x emissions per state per month from 2001 to 2015. To report the total CO_2, SO_2, 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 CO_2, SO_2, 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 hydropower, 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 CO_2, SO_2, 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). CO_2 percentages are relative to totals from the electricity sector. SO_2 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.

	CO_2		SO_2		NO_x	
State	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 CO_2, SO_2, 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 CO_2 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 CO_2 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 CO_2, 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' CO_2 emissions in our statistical model, but no changes in SO_2 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 SO_2 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 SO_2 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 CO_2 emissions during droughts (table 1).

We estimate the total 2001–2015 drought-induced emissions over the western US to be 100.1 Mt of CO_2, 44.8 kt of SO_2, and 56.9 kt of NO_x. The annual-mean increase in regional CO_2 (6.7 Mt of CO_2/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 CO_2 emissions relative to climate mitigation targets. Median estimates of yearly CO_2 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 CO_2 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 CO_2, 0.3 kt of SO_2, 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 CO_2 emissions targets. Table 2 shows annual-mean (2001–2015), state-level drought-induced CO_2 emissions as percentages of (1) the states' total emissions from the electricity sector between 2001–2015, (2) targets of annual CO_2 rates established by the Clean Power Plan (CPP) (EPA 2015), and (3) state-specific targets of yearly CO_2 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 CO_2, SO_2, 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 CO_2 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 heterogenous 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 heterogenous 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 thermoelectric 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.

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