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Key Points:

- Modeling analysis of future hydrologic droughts over U.S. is provided
- Relative contributions from climate change and water managements are quantified
- Future hydrologic drought will be alleviated by reservoirs but intensified by local water extraction

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Hydrological Drought in the Anthropocene: Impacts of Local Water Extraction and Reservoir Regulation in the U.S.

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Abstract Hydrological drought is a substantial negative deviation from normal hydrologic conditions and is influenced by climate and human activities such as water management. By perturbing the streamflow regime, climate change and water management may significantly alter drought characteristics in the future. Here we utilize a high-resolution integrated modeling framework that represents water management in terms of both local surface water extraction and reservoir regulation and use the Standardized Streamflow Index to quantify hydrological drought. We explore the impacts of water management on hydrological drought over the contiguous U.S. in a warming climate with and without emissions mitigation. Despite the uncertainty of climate change impacts, local surface water extraction consistently intensifies drought that dominates at the regional to national scale. However, reservoir regulation alleviates drought by enhancing summer flow downstream of reservoirs. The relative dominance of drought intensification or relief is largely determined by the water demand, with drought intensification dominating in regions with intense water demand such as the Great Plains and California, while drought relief dominates in regions with low water demand. At the national level, water management increases the spatial extent of extreme drought despite some alleviations of moderate to severe drought. In an emissions mitigation scenario with increased irrigation demand for bioenergy production, water management intensifies drought more than the business-as-usual scenario at the national level, so the impacts of emissions mitigation must be evaluated by considering its benefit in reducing warming and evapotranspiration against its effects on increasing water demand and intensifying drought.

1. Introduction

Droughts are often perceived as natural hazards, which produce a complex web of impacts that span many sectors of the society and environment, including water supply, agriculture, energy, water quality, and riparian habitats (Mishra & Singh, 2010; Warwick, 1975; Wilhite et al., 2000). Droughts can be classified into meteorological, agricultural, hydrological, and socioeconomic droughts (Mishra & Singh, 2010; Wang et al., 2011; Wilhite & Glantz, 1985). This study explores hydrological drought, which is characterized by streamflow deficit.

Both climate anomalies, such as rainfall deficit and increased evapotranspiration, and human activities, such as water management, can affect streamflow and hence hydrological drought. Previous studies projected increasing droughts in a warmer climate over different regions despite large uncertainties about how drought is changing regionally and globally (e.g., Cooley et al., 2015; Dai, 2011; Prudhomme et al., 2014; Seneviratne et al., 2012; Sheffield & Wood, 2008). Warming climate leads to more winter rainfall instead of snow, earlier snowmelt, and decreases in spring and summer streamflow, which may lead to increase in hydrological droughts (e.g., Barnett et al., 2008; Prudhomme et al., 2014). Besides climate change, Wada et al. (2013) found that increasing human water consumption is also an important mechanism for intensifying hydrological droughts. Over the period 1960–2010, global human water consumption increased almost two and a half times due to the expansion of agricultural, soaring temperature accompanied by global warming, rapid growth of population, and increased standard of living. Higher water consumption can reduce runoff and streamflow to trigger local hydrological drought conditions. Although the droughts are triggered by natural processes, the anthropogenic influences, such as water demands, have direct impacts on hydrological drought in comparison to other forms of drought. As one of the drought adaption strategies, water management infrastructure such as dams and reservoirs are built while the population grows. Contrary to water consumption, reservoir regulations are designed to stabilize streamflow and buffer hydrological drought by increasing water supply reliability (Wada et al., 2013; Wen et al., 2011; Zhang et al., 2015; Zilberman et al., 2011).

In general, droughts are defined based on hydrometeorological variables but such definitions fail to incorporate anthropogenic influences in the analysis. As noted by Mishra and Singh (2010), even with a similar amount of annual precipitation, a region with higher population will be more susceptible to drought than a region with lower population because of differences in water demand. Drought conditions defined using drought indices based on precipitation alone will reflect similar droughts in the two regions, despite the vastly different drought vulnerability due to population differences. Therefore, anthropogenic factors (i.e., water demand) must be incorporated in drought analysis. Several studies evaluated the potential influence of climate change on droughts (Burke & Brown, 2010; Burke et al., 2006; Dai, 2013; Lehner et al., 2006; Mishra & Singh, 2009; Trenberth et al., 2014; Wang, 2005). More recently, several studies further evaluated the potential influence of anthropogenic emissions (warming) on droughts (Cheng et al., 2016; Cook et al., 2015; Diffenbaugh et al., 2015; Williams et al., 2015). However, few studies consider the potential influence of anthropogenic factors such as water demand, reservoir regulation, and land use change that have direct influence on hydrological droughts.

Recent drought research has emphasized the role of climate drivers, but drought management and quantification can be improved by adopting an integrated framework that considers both human and climate factors (Mishra & Singh, 2010; Rajsekhar et al., 2015a, 2015b; Van Loon, Gleeson, et al., 2016). Wanders and Wada (2015) evaluated human and climate impacts on future hydrological drought globally. In their assessment of future drought scenario, land use and population density were assumed to be constant over time. However, water demand, hence water consumption and water management, will change with the socioeconomic changes embedded in the emissions scenarios that drive climate changes, so assuming no change in water demand introduces inconsistencies in integrated modeling to delineate climate change and water management effects. In addition, modeling reservoir operations based on water demand objective alone may lead to an overall underestimation of reservoir regulation effect because a large fraction of reservoirs are operated for multiple, contrasting objectives such as flood control and irrigation. Hejazi et al. (2015) compared the relative impacts of changing water demand and climate change on water stress. They concluded that emissions mitigation could increase water stress by increasing water demand for irrigation, and this impact outpaces the benefits from emission mitigation in the United States in the 21st century. However, their work did not analyze the drought changes. There are a few recent studies focusing on drought in the human-influenced era and advocated for new definitions of drought to include the role of human (Mishra & Singh, 2010; Van Loon, Gleeson, et al., 2016; Van Loon, Stahl, et al., 2016).

As climate change and human activities continue in the future, understanding their influence on future hydrological droughts is imperative for sustainable water use and drought adaptation. This study uses a high-resolution integrated modeling framework over the contiguous U.S. (CONUS) to simulate the relative and combined impacts of climate change and water management on hydrological drought for historical and future periods. Two emissions scenarios driving different climate change and water demand are considered: Representative Concentration Pathway (RCP) 4.5 and 8.5. For drought assessment, we use a standardized hydrological drought index to explore changes in drought characteristics at seasonal and annual time scales and different intensity levels.

2. Methods

2.1. Modeling Framework

This study adopts an integrated regional modeling framework that couples a regional implementation of version 4.0 of the Community Land Model (CLM) (Lawrence et al., 2011; Oleson et al., 2010), a river routing model called the Model for Scale Adaptive River Transport (MOSART) (Li, Wigmosta, et al., 2013), a Water Management model (WM) (Voisin, Liu, et al., 2013), and a regional implementation of the Global Change Assessment Model (GCAM) that simulates water demands, among other socioeconomic components

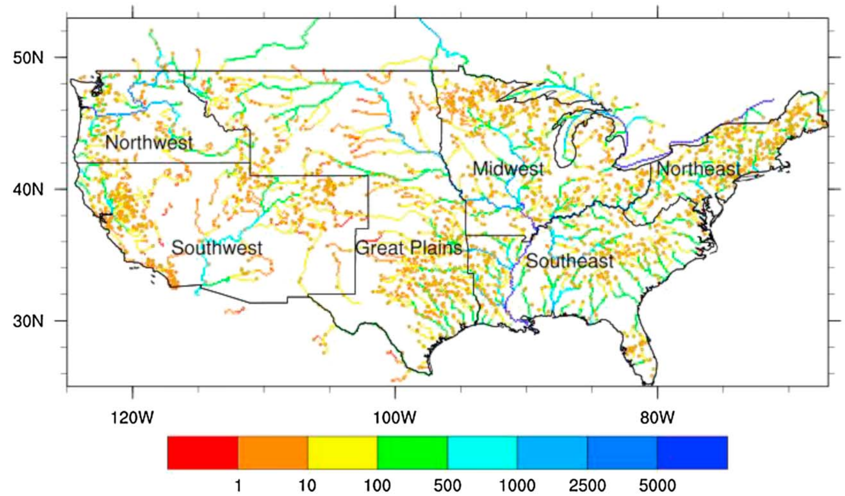

Figure 1. The location of reservoirs along with reservoir downstream river network at 1/8th degree resolution. Reservoir locations are marked by the golden dots. The river network is displayed along with the average monthly natural streamflow simulated for the historical period under natural flow condition. The locations, storage capacities, and reservoir regulation objectives of the 1839 reservoirs are retrieved from the GRanD database. For regional analysis, CONUS is split into six regions defined by the National Climate Assessment.

(Hejazi et al., 2014). Detailed descriptions on the model components and their coupling in an integrated modeling framework can be found in Voisin, Li, et al. (2013), Voisin, Liu, et al. (2013), Li et al. (2015), and Kraucunas et al. (2015).

The WM model includes a surface water extraction module and a reservoir regulation model. The surface water extraction module withdraws surface water to meet the water demand simulated by GCAM. Within each grid, the daily water demand is first met by withdrawing water from the local surface runoff and river channel storage with the constraint to leave at least 50% of the flow in the main channel for computational stability in the routing model. Then the demand is met by water supply from the dependent reservoirs associated with the grid according to reservoir operating rule (Voisin, Li, et al., 2013). If the water demand on a given day is still not fully met, the remaining demand is fulfilled by assuming an unlimited groundwater supply. A reservoir dependency database assigns the spatial dependency between reservoirs and the model grids on water demand and supply. The reservoir module defines three types of reservoir operating rules (irrigation, flood control and other purposes, and combined irrigation and flood control) for flood control and providing water to each dependent grid with water demand (Voisin, Li, et al., 2013). Reservoir release for nonirrigation is based on the mean annual flow and initial reservoir storage of each operational year. For irrigation reservoir, the reservoir targets are adjusted to include monthly variability of both inflow and demand. For joint flood control and irrigation purposes reservoir, the planned irrigation releases are further adjusted during the period before snowmelt with an additional release to allow a linear drop in storage. In this study, 1,839 reservoirs retrieved from the GRanD database (Lehner et al., 2011) were represented by the WM model and integrated in the hydrological drought analysis.

2.2. Experiments Design

The coupled CLM, MOSART, and WM models were driven by atmospheric forcing simulated by a regional Earth System Model (Kraucunas et al., 2015) based on the Weather Research and Forecasting model (Skamarock et al., 2008) coupled to CLM. The regional Earth System Model was driven by the Community Earth System Model (Gent et al., 2011) with its output retrieved from the Coupled Model Intercomparison Model Phase 5 (CMIP5) (Taylor et al., 2012). The regional simulations were bias corrected for temperature and precipitation based on observations following the approach of Wood et al. (2004). CLM was spun up by cycling the meteorological forcing over the historical period until all variables reached an equilibrium. In this study, the coupled model was applied to CONUS at an hourly time step and all results are archived daily for analysis at 1/8th degree (~12 km) over a historical (1980 to 2004) and a future period (2008 to 2095), as adopted in Hejazi et al. (2015). A map of the modeling area including the locations of reservoirs

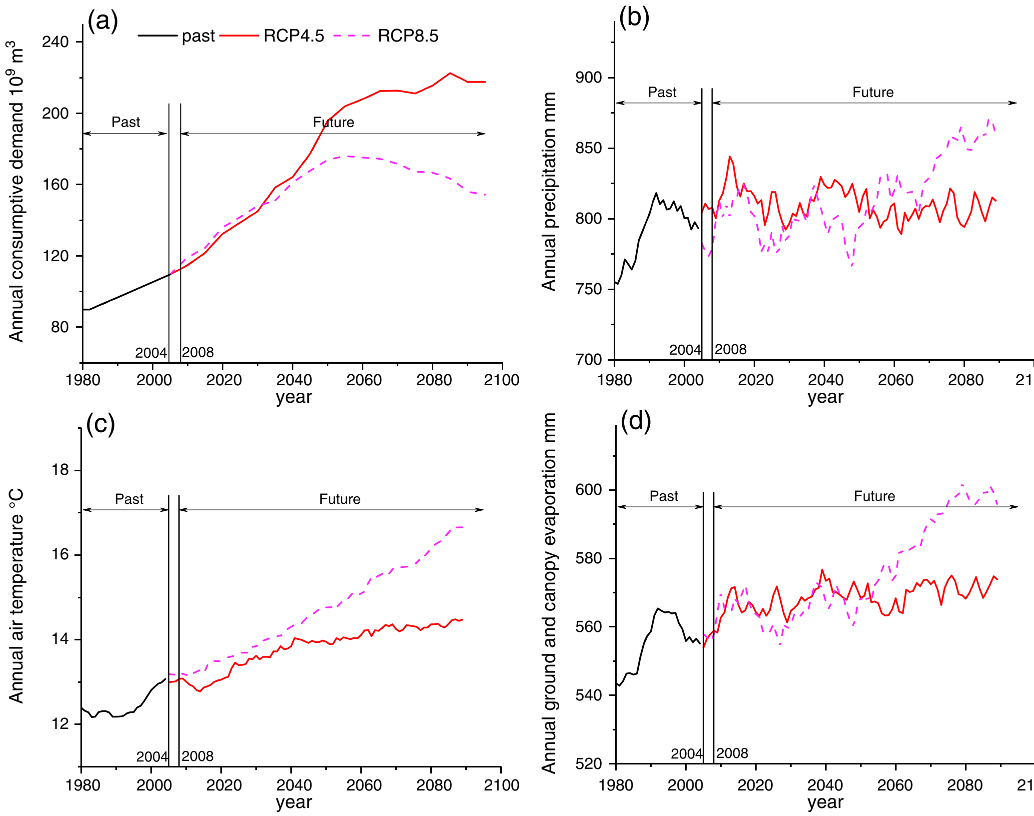

Figure 2. (a) Annual consumptive water demand and 10 year smoothed, (b) annual total precipitation, (c) air temperature, and (d) ground and canopy evaporation averaged over the contiguous U.S. from 1980 to 2095. Simulations for the historical period and future periods are shown in black and red or magenta, respectively, for RCP4.5 (full lines) and RCP8.5 (dashed lines).

is shown in Figure 1. Two emissions scenarios are considered in the future period: Representative Concentration Pathway (RCP) 4.5 and 8.5. The RCP4.5 and RCP8.5 scenarios correspond to global radiative forcing levels of 4.5 and 8.5 W/m^2 by the end of the 21st century with the former featuring climate change mitigation with lower greenhouse gas emissions and more bioenergy use, and the latter represents a business-as-usual scenario. Figure 2 shows the time series of total annual precipitation simulated by the Regional Earth System Model and the water demand simulated by GCAM as inputs to CLM-MOSART-WM for the historical and future periods under the two emissions scenarios. To isolate the human influences from the impacts of climate change, the model was run with and without the WM model separately, and the simulations are denoted as WM and NM, respectively. Monthly streamflow for the historical period without WM (his_NM) and future periods with and without the WM for RCP8.5 (S85_NM and S85_WM) and RCP4.5 (S45_NM and S45_WM) were used in the hydrological drought analysis.

2.3. Drought Analysis Method

There are multiple drought indices that are used to represent different types of droughts as well as integrated form of droughts. For example, univariate drought indices only consider one specific physical form of drought: hydrological, meteorological, or agricultural (Mishra & Singh, 2010), whereas multivariate drought indices can able to capture more than one form of drought (Hao & AghaKouchak, 2013; Rajsekhar et al., 2015b, 2015a) or socioeconomic drought (Mehran et al., 2017, 2015). However, the selection of appropriate drought indices is often confusing, and it tends to be selected based on the necessity of stakeholders as well as natural of research questions to be addressed. In our study, we used standardized streamflow index (SSI) for drought assessment, because reservoir regulation and water management largely depends on streamflow. In addition to that streamflow data have been widely applied for hydrologic drought analysis (Clausen & Pearson, 1995; Dracup et al., 1980; Sadeghipour & Dracup, 1985).

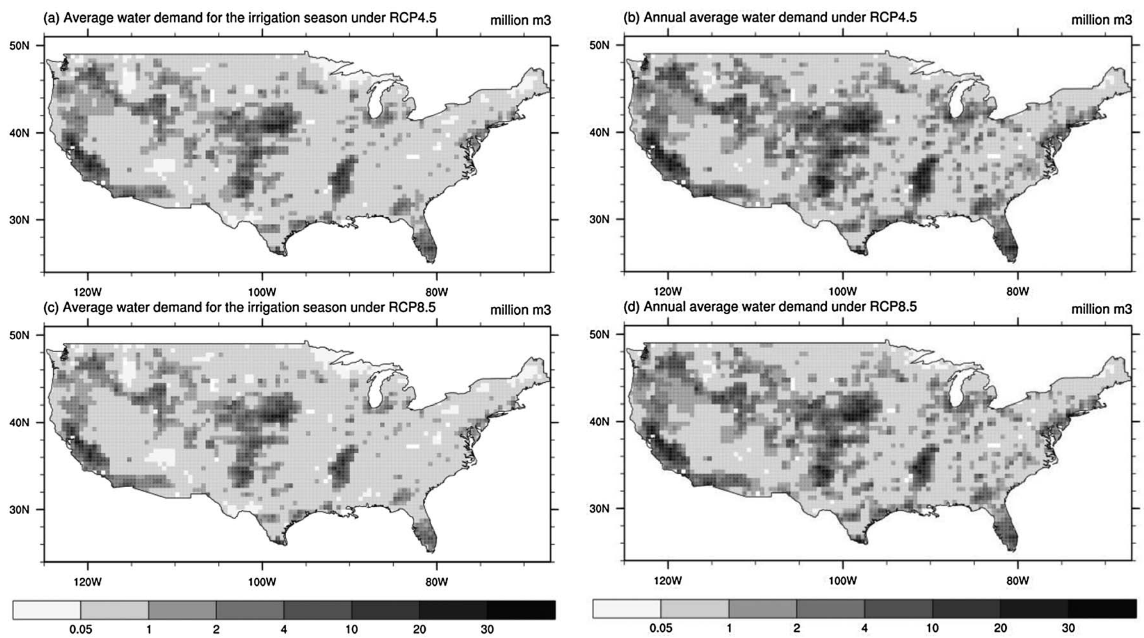

Figure 3. Long-term average water demand in (a, c) summer (JAS) and (b, d) the whole year over the period 2008–2095. Demand in JAS makes up approximately 54% of the annual water demand.

For drought management, quantification of hydrological drought is essential. Up till now, two types of hydrological drought indices have been developed, including the standardized drought indices (Shukla & Wood, 2008; Wang et al., 2011; Yuan et al., 2016) and threshold level-based percentile streamflow (He et al., 2017; Hisdal & Tallaksen, 2003; Wanders et al., 2015). The standardized drought indices (e.g., SSI) has its own advantages over other drought indices (Mishra & Singh, 2010; Van Loon, 2015) in that (a) it is derived using single-variable (e.g., streamflow) records alone, so drought analysis is possible if other hydrometeorological observations are not available for a given region, (b) it is flexible and various time scales can be chosen depending on the users' need, and (c) due to its standardization, drought quantifications at any time scale are consistent, and the drought characteristics (e.g., severity and duration) can be compared within and among different locations.

In this study, hydrological drought was quantified using the Standardized Streamflow Index (SSI) (Shukla & Wood, 2008; Vicente-Serrano et al., 2011; Zhang et al., 2015), which is conceptually similar to Standardized Precipitation Index (McKee et al., 1993). To compute the SSI, we first estimated the probability density function that describes the long-term time series of observed streamflow. Note that streamflow is simulated by MOSART based on routing of both surface and subsurface runoff simulated by CLM so a drought index based on streamflow represents both surface and subsurface hydrologic conditions. Previous studies (Li, Xiong, et al., 2013; López-Moreno et al., 2009; Lorenzo-Lacruz et al., 2010; Vicente-Serrano, 2006) showed that the Pearson type III (P3) distribution provides a suitable fit for the monthly streamflow series for calculation of the SSI. To obtain the SSI, the P3 distribution was used to fit the baseline historical natural (i.e., his_NM) monthly streamflow series. Any base time of the projected streamflow time series may be chosen, depending on the time scale of interest. In the present study, running series of total streamflow corresponding to 3 and 12 months were used and the corresponding SSIs were calculated. Once the probability density function was determined, the cumulative probability of the projected streamflow amount was computed. Lastly, the inverse normal (Gaussian) function, with zero mean and unit variance, was applied to the cumulative probability distribution function to generate the SSI.

In this study, the 12 month SSI (SSI12) was used for drought event detection, while the 3 month streamflow total (July–August–September), denoted as SSI3_JAS, was used to indicate the seasonal loss in streamflow during the irrigation season (Nalbantis & Tsakiris, 2009). The 12 month SSI was adopted since it can capture the climatological variations well and eliminate the disturbance from minor droughts with short duration and

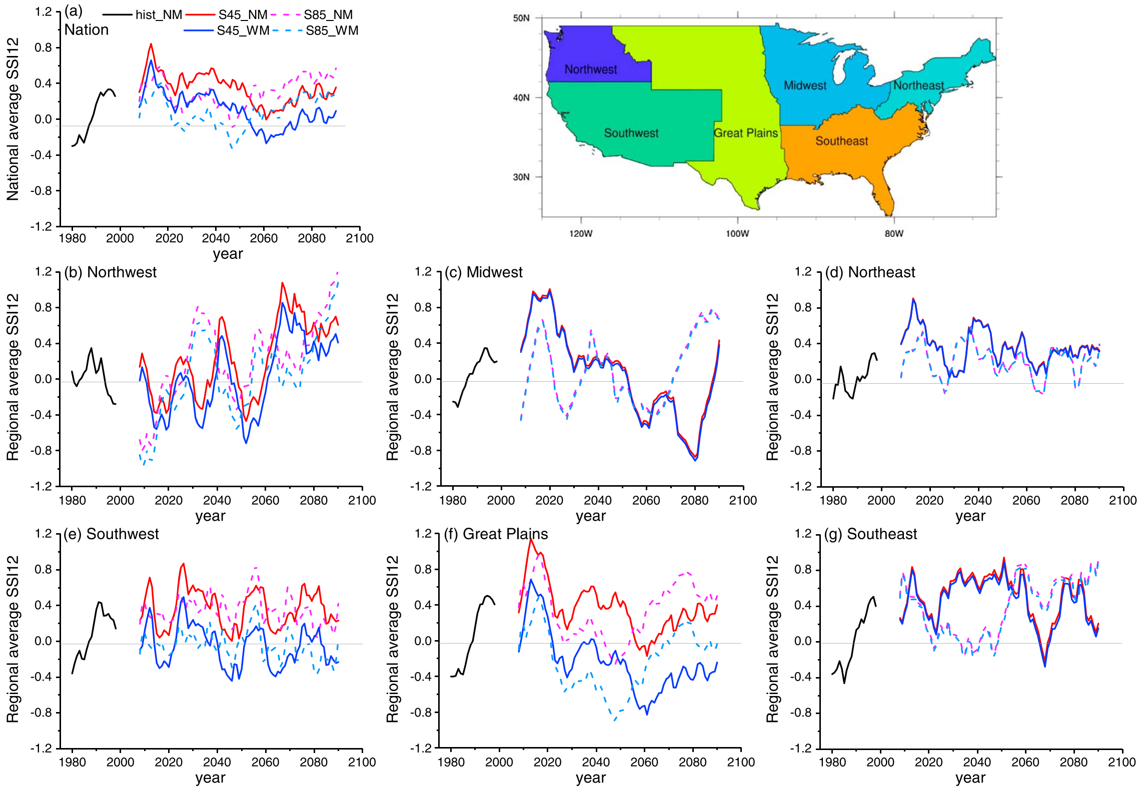

Figure 4. Time series of 10 year smoothed annual averaged SSI12 for the historical period 1980–2004 (black) and four future scenarios under RCP4.5 (solid) and RCP8.5 (dashed) with (blue) and without (red) water management over the period 2008 to 2095 for (a) the nation and six regions including (b) northwest, (c) Midwest, (d) Northeast, (e) Southwest, (f) Great Plains, and (g) Southeast. Simulations for the historical and future periods are labeled as "hist" and "S45" and "S85" for RCP4.5 and RCP8.5, and simulations with and without water management are labeled as "NM" and "WM", respectively. The difference between the blue and red lines reflects the effects of water management, while the difference between the solid and dashed lines indicates the effects of emissions mitigation. All SSI series are computed with respect to the historical natural condition.

low magnitude. Drought spatial extent defined as the percentage area where drought event (SSI < -1.0, indicating the deviation from average conditions exceeds one standard deviation) occurs at least once a year was calculated each year. Generally, a continuous period of at least 30 years is needed to compute robust extreme statistics (McKee et al., 1993), but a 25 year historical period from 1980 to 2004 was used in our analysis due to limited availability of the high-resolution climate model output. The standardization of the SSI ensures that the frequencies of extreme events at any location and at any time scale are consistent.

To quantify the changes of hydrological drought frequency due to water management, a statistical binomial test was applied. The SSI series of each grid over the period 2008 to 2095 was first divided into two sets, natural condition (SSI_NM, p_1) and water management condition (SSI_WM, p_2), each transformed to a binomial distribution, that is, drought state (success, SSI < -1.0) or nondrought state (failure, SSI ≥ -1.0). Then the difference of the two series was estimated using the two sample one-tailed binomial test with a 95% confidence level.

We used the test statistic $z = \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p}(1-\hat{p})\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}$, where $\hat{p} = \frac{n_1\hat{p}_1 + n_2\hat{p}_2}{n_1+n_2}$, with a critical value $z_{0.05}$=1.645 to test the following hypotheses:

1. Drought frequency is alleviated by water management: H_0: $p_1 > p_2$, H_1: $p_1 \leq p_2$. The null hypothesis is rejected if $z \leq -z_{0.05}$.
2. Drought frequency is intensified by water management: H_0: $p_1 < p_2$, H_1: $p_1 \geq p_2$. The null hypothesis is rejected if $z \geq z_{0.05}$.

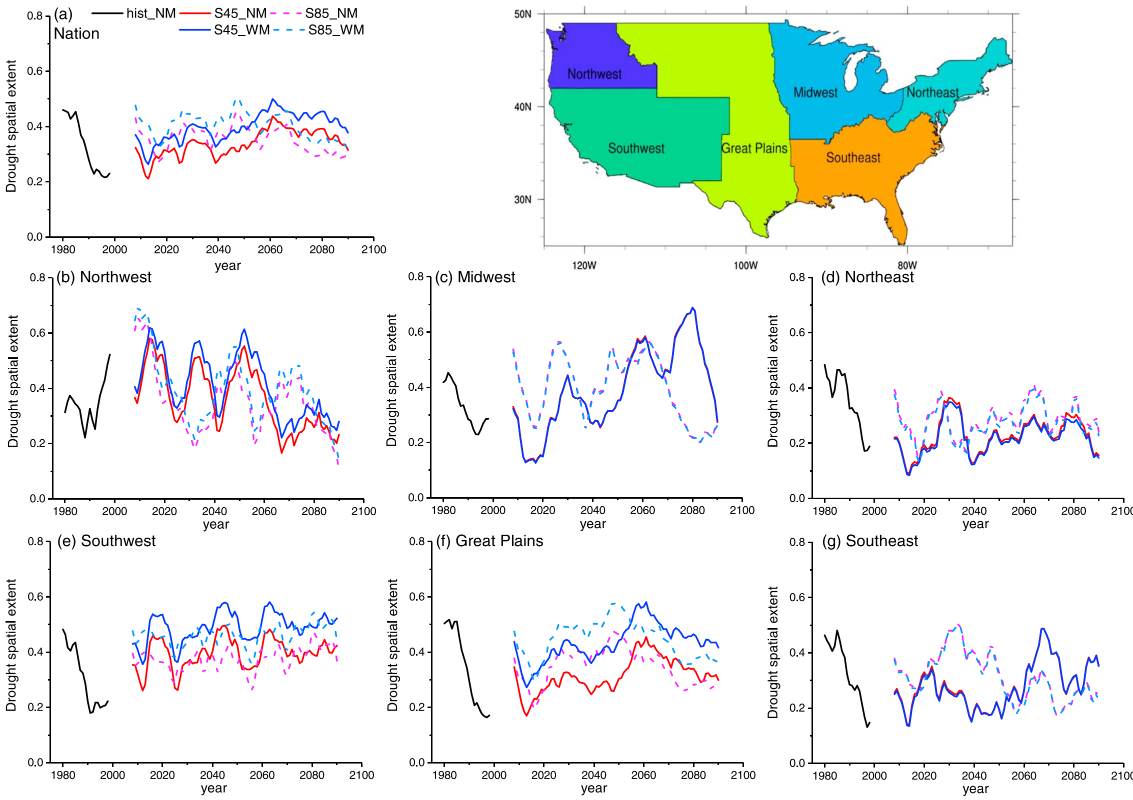

Figure 5. Time series of 10 year smoothed drought spatial extent (SSI12 < -1.0) for the historical period 1980–2004 (black) and four future scenarios under RCP4.5 (solid) and RCP8.5 (dashed) with (blue) and without (red) water management over the period 2008 to 2095 for (a) the nation and six regions.

3. Results

Figure 2a shows that water demand in the two scenarios diverges after the midcentury. The decreasing water demand in RCP8.5 is driven by population decline, while in RCP4.5, increasing water demand for bioenergy production for emissions mitigation counters the decrease in water demand due to changes in human population (see Hejazi et al. (2015) for more details). The projected spatial distributions of summer season and annual water demand are shown in Figure 3. Areas of intensive water demand are predominantly in the irrigation regions, such as the Great Plains and western U.S. The time series of 10 year smoothed temperature show an overall warming climate for both RCPs for the U.S. (Figure 2c). The response of precipitation to climate change is generally small compared to the large interannual-to-decadal variability. Before the midcentury, precipitation is higher under RCP4.5 than RCP8.5, but after the midcentury, precipitation is obviously higher in RCP8.5 than RCP4.5 (Figure 2b). In response to the changes in temperature and precipitation as well as other meteorological variables (not shown), the evapotranspiration exhibits temporal variability comparable to that of precipitation, but as evaporative demand increases with warmer temperature, evapotranspiration is generally predicted to increase for both RCPs (Figure 2d).

3.1. Impacts of Climate Change on Hydrological Drought

Figure 4 compares time series of 10 year smoothed annual averaged 12 month SSI, denoted as SSI12, calculated from simulations in the historical and future periods with and without water management over CONUS (Figure 4a) and six U.S. regions (Figures 4b–4g) defined by the National Climate Assessment (http://nca2014.globalchange.gov) (Kunkel et al., 2013; Melillo et al., 2014). Over the historical period (1980–2004), the model simulated an overall increase in streamflow similar to the observed trend reported in previous studies (Dai, 2011; Sheffield et al., 2012). In the future period (2008–2095), both the SSI12 and drought pattern based on the high emissions scenario (RCP8.5) and the emissions mitigation scenario (RCP4.5) show clear regional and temporal differences (Figures 4 and 5). The SSI12 under RCP4.5 shows a continuous drying (< -1/decade)

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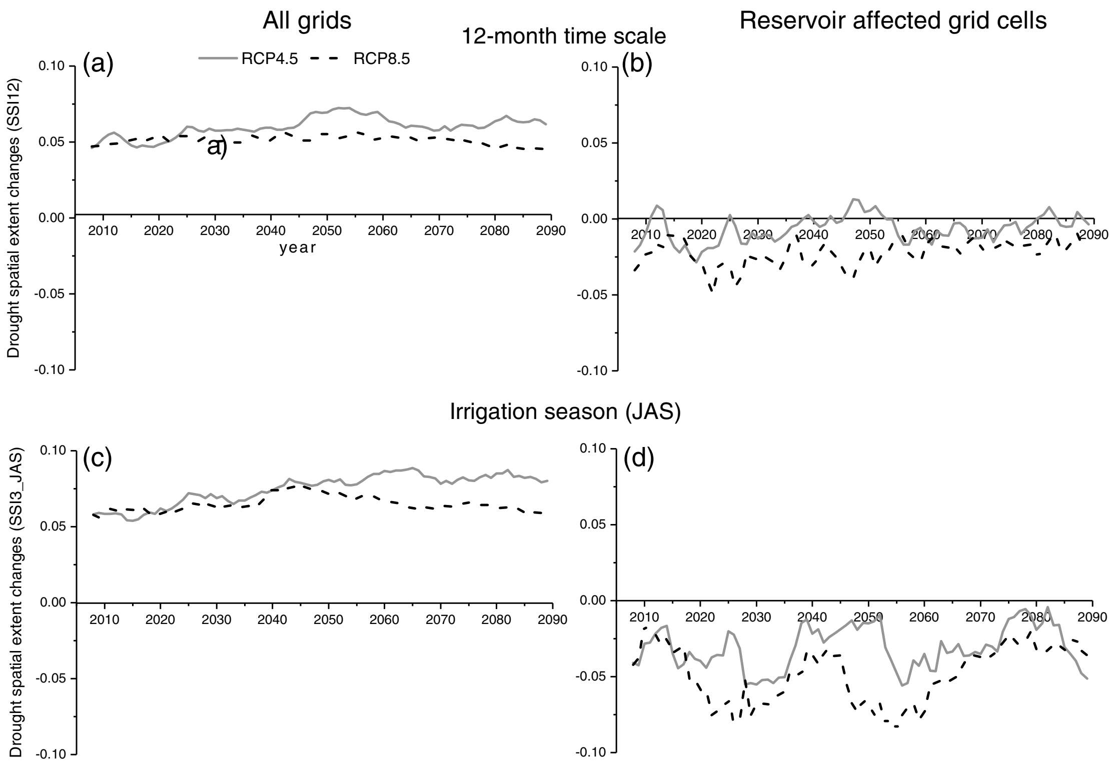

Figure 6. Time variations of the 10 year smoothed drought spatial extent changes due to water management (e.g., RCP4.5_WM minus RCP4.5_NM) for (left) all grids in the contiguous U.S. and (right) reservoir affected grid cells. Results are shown at (a, b) 12 month time scale and for the (c, d) irrigation season (JAS), under RCP 8.5 (dashed) and RCP4.5 (solid). SSI12 and SSI3_JAS are used to investigate hydrological drought for the annual time scale and the irrigation season (JAS), respectively.

through the midcentury across much of the Midwest and Great Plains. In contrast, the SSI12 under RCP8.5 shows no apparent trend in the 21st century. The SSI12 multidecadal variability reflects changes in runoff that are dominated by changes in precipitation, despite the monotonic increase in temperature and evapotranspiration, which is more significant in RCP8.5 compared to RCP4.5 (Figure 2). Overall, at the national scale, there is no statistically significant long-term trend of SSI12 under either RCP4.5 or RCP8.5 based on climate projections by a single climate model because of the large decadal variability in precipitation and runoff.

3.2. Impacts of Water Management on Hydrological Drought

Human activities are quantified by the water management model, which includes modules to represent local surface water extraction and reservoir regulation. Local extraction is mainly controlled by water demand, while reservoir regulation incorporates both water demand and flood control regulations for the downstream areas. Simulations with and without water management are compared to evaluate the effects of water management on hydrological droughts in terms of drought magnitude, spatial extent, frequency, and severity level.

3.2.1. Drought Magnitude and Spatial Extent

Comparing simulations with and without water management, the net effect of local extraction and reservoir regulation is rather stationary over time (Figure 4). At the national scale, water management reduces the annual averaged SSI12 by as much as 0.129 to 0.315 year^{-1}, indicating clearly an overall drying effect by human activities. At the regional scale, the drying effect of water management is most obvious in the Southwest and Great Plains, but the effect is negligible in the Midwest, Northeast, and Southeast. These regional differences are driven by the regional differences in consumptive water demand, which is dominated by irrigation and significantly larger in the Great Plains and California (Figures 3b and 3d). The drying effect also manifests in the increased spatial extent of hydrological drought both nationally and regionally (Figure 5). One may observe from Figures 4 and 5 that the magnitude of the difference caused by water

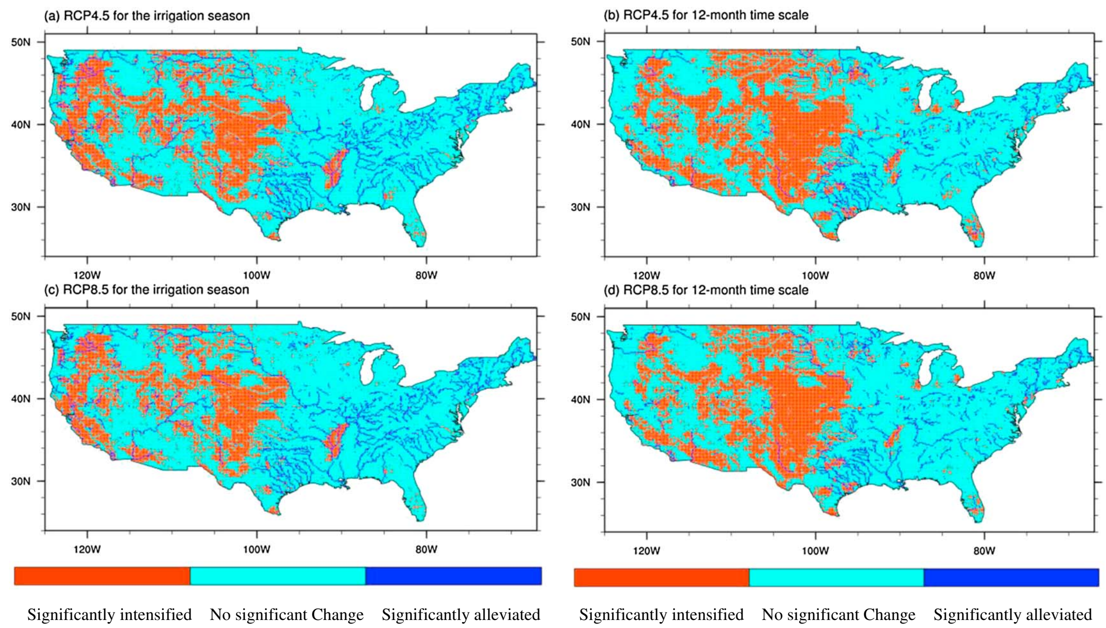

Figure 7. Drought frequency changes due to water management for (a, c) JAS and (b, d) 12 month time scale calculated as the difference between SSI_NM and SSI_WM, over the period 2008 to 2095 under RCP4.5 (Figures 7a and 7b) and RCP8.5 (Figures 7c and 7d). The red and blue colors denote grid cells with statistically significant increase and decrease in drought frequency, respectively, and cyan denotes grid cells with no significant change in drought frequency. Statistical significance is determined using the binomial test for $P \leq 0.05$.

management is generally less than the interannual fluctuations in the historical or future periods. However, the former is more consistent over time and between RCP4.5 and 8.5, indicating the deterministic mechanisms, while the latter is due to climate variability that influences streamflow and is inherently unpredictable in the context of long-term climate projection.

To distinguish the effects of local extraction from those of reservoir regulation, Figure 6 presents the spatial extents of hydrological droughts over CONUS (denoted as “all grids” with 52250 grid points) and areas downstream of reservoirs (denoted as “reservoir affected grid cells” with 9161 grid points) separately. Since July–August–September (JAS) is a season with low streamflow but high water demand, as the JAS irrigation water demand is approximately 54% of the annual total, the 3 month SSI for this irrigation season (SSI3_JAS, see Figures 6c and 6d) is comparable to the SSI12 at the annual scale (SSI12, see Figures 6a and 6b).

At the national scale, water management continuously intensifies drought spatial extent under both RCP4.5 and RCP8.5 throughout the 21st century (Figures 6a and 6c). Comparing the two figures, the increase in drought spatial extent is more significant in the irrigation season than the annual average. For areas downstream of reservoirs (Figures 6b and 6d), water management alleviates rather than increases drought spatial extent, particularly in the irrigation season. The opposite effects of water management for all grids and reservoir affected grid cells can be explained by the dominance of local extraction across CONUS, which intensifies drought, while reservoir regulation generally increases streamflow during the summer low flow period, hence alleviating drought in areas downstream of reservoirs. However, in the nonirrigation season particularly winter, reservoir regulation reduces the release of water to downstream areas so it intensifies drought through reservoir storage. The drought relief effect of reservoirs in the summer irrigation season is partially offset by the drought intensifying effect in winter, but reservoirs still provide an overall drought relief effect at the annual scale.

Comparing between RCP4.5 and RCP8.5, drought is intensified more at all grid cells and alleviated less at the reservoir affected grid cells in RCP4.5 compared to RCP8.5. This stems from the difference in water demand between the two scenarios driven primarily by the larger irrigation demand for biofuel crops in RCP4.5 for emissions mitigation (Figure 2a). This is elucidated further by analysis of drought frequency discussed next.

Table 1
Binomial Test Results (P ≤ 0.05) for Drought Frequency Changes (Nondrought or Drought) Due To Water Management Over the Period 2008 to 2095

		SSI3_JAS			SSI12		
Grid type		Intensified	Alleviated	Unchanged	Intensified	Alleviated	Unchanged
Reservoir affected grid cells	RCP4.5	1299	4242	3620	1970	2818	4373
	RCP8.5	1097	4300	3764	1872	2973	4316
All grid cells	RCP4.5	13462	4273	34515	17023	2831	32396
	RCP8.5	12315	4322	35613	15638	2983	33629

Note. The table shows the numbers of grid cells with drought frequency significantly intensified, alleviated, or unchanged because of water management in the RCP4.5 and RCP8.5 scenarios for reservoir affected grid cells and for all grids, respectively.

3.2.2. Drought Frequency

Figure 7 shows the spatial distribution of areas with significant changes in drought frequency. The changes are consistent with the spatial distribution of water demand (Figure 3), both showing increase in heavy agricultural production regions of the Great Plains and western U.S. Table 1 lists the numbers of grid cells experiencing statistically significant changes in drought frequency induced by water management (see supplementary for details on statistical test of significance). For CONUS at the 12 month scale, 32.6% and 29.9% of the areas experience significant intensification of drought frequency by water management under RCP4.5 and RCP8.5, respectively. Areas that experience significant alleviation of drought frequency constitute only 5.4% and 5.7% of CONUS, although both are approximately 1.5 times higher in JAS compared to the annual scale. Interestingly, unlike the numbers of grid cells with intensified drought frequency that increase significantly from reservoir affected grid cells to all grids, the numbers of grid cells with reduced drought frequency

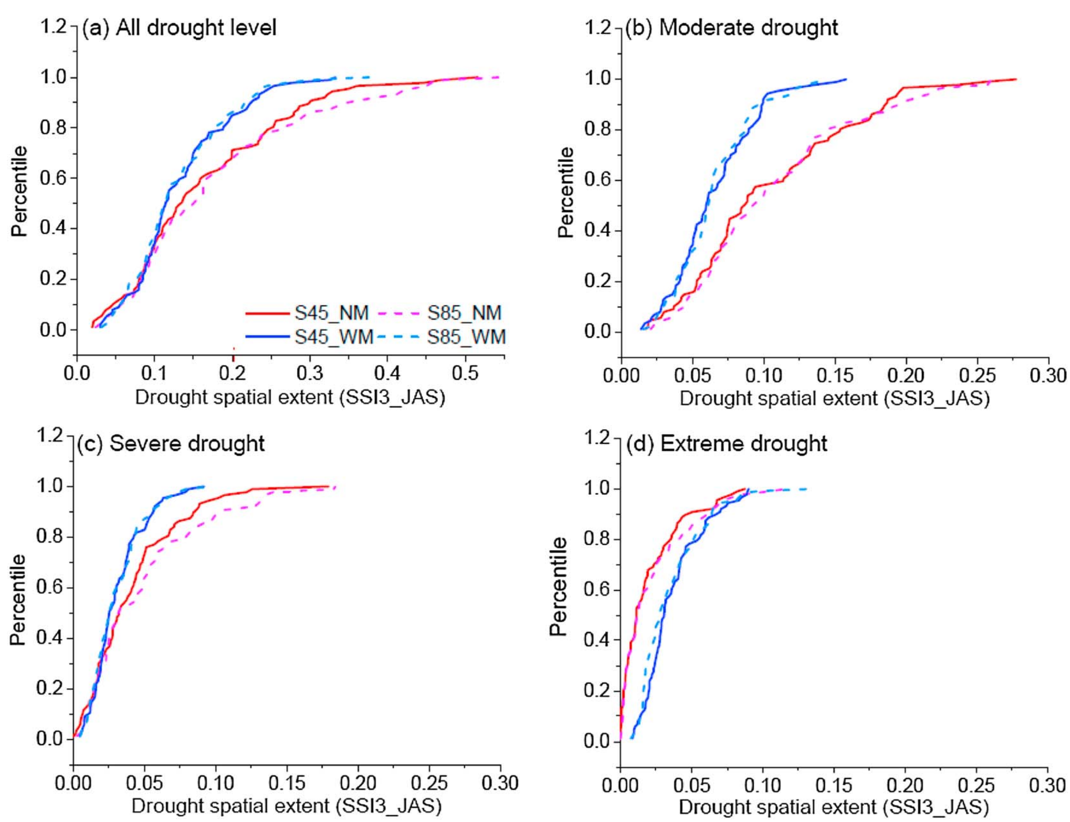

Figure 8. Empirical cumulative density function (CDF) of the drought spatial extent in JAS for reservoir affected grid cells over the period 2008–2095 corresponding to (a) all drought level (SSI < −1); (b) moderate drought (−1.00 < SSI < −1.5); (c) severe drought (−1.5 ≤ SSI < −2.0); and (d) extreme drought (SSI ≤ −2.0). Results are shown for simulations with (blue) and without (red) water management and for the RCP4.5 (solid) and RCP8.5 (dashed) scenarios.

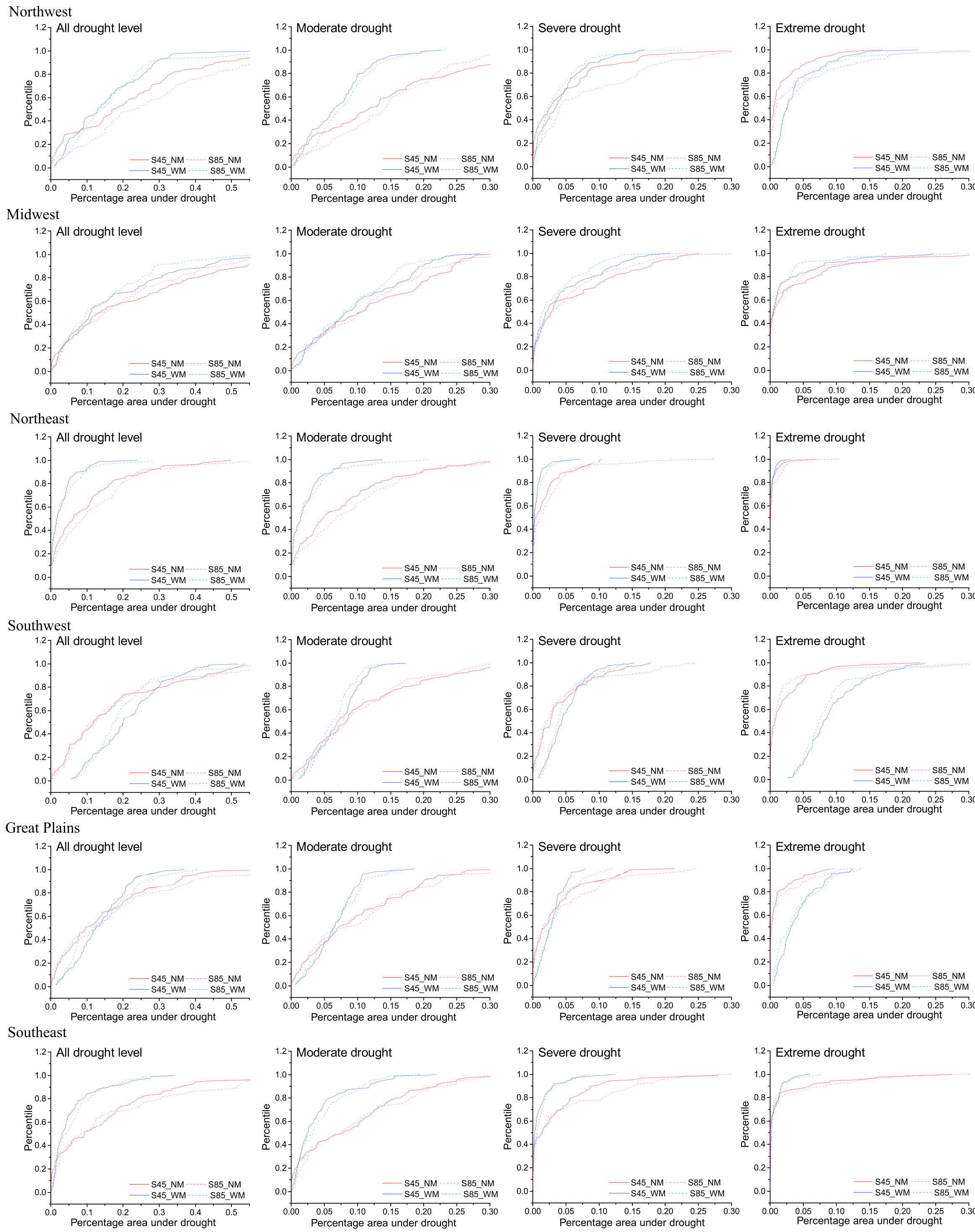

Figure 9. Regional results of empirical cumulative density function (CDF) of the annual drought spatial extent in JAS for reservoir affected grid cells over the period 2008–2095. The first column is all drought level (SSI < -1) results; second column is moderate drought ($-1.00 <$ SSI < -1.5) results; third column is severe drought ($-1.5 \leq$ SSI < -2.0) results; and the fourth column is extreme drought (SSI ≤ -2.0) results.

are almost the same between the two sets of grid cells, suggesting that drought relief is mainly associated with areas downstream of reservoirs. This inference is supported by the spatial distribution of drought frequency changes (Figure 7), which shows that the areas with significant drought frequency alleviation generally overlap with the river network affected by reservoirs (Figure 1).

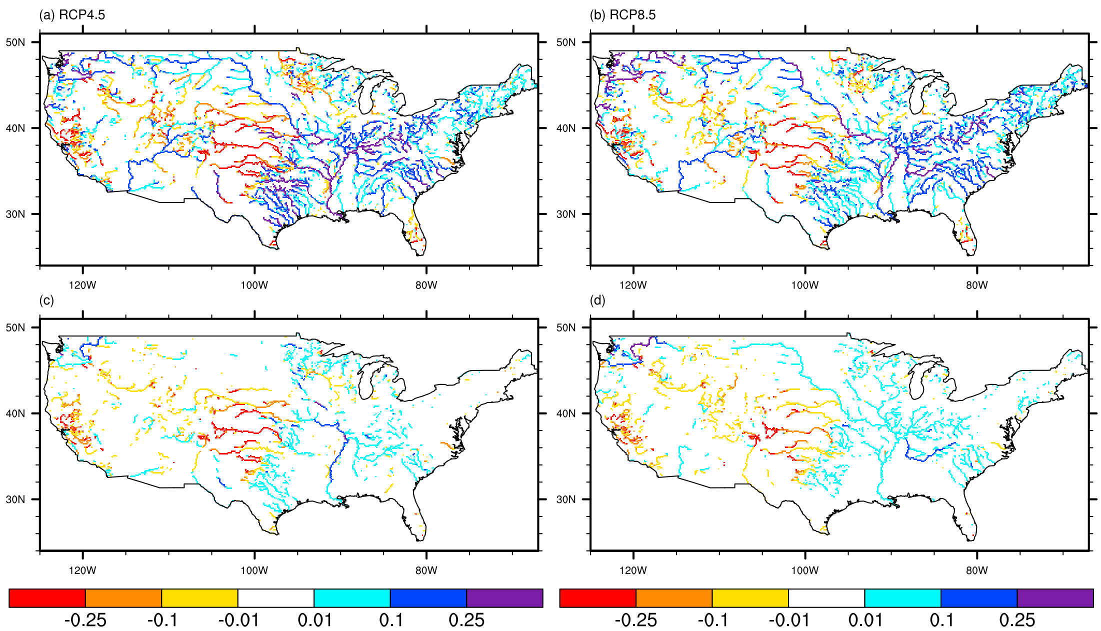

Figure 10. Drought frequency changes in reservoir affected grid cells induced by water management during the irrigation season: Under (a, c) RCP4.5 and (b, d) RCP8.5 over the period 2060–2095 when the water demand difference between the two scenarios is more pronounced. The shift in drought pattern is displayed as the fraction of years (during 2060–2095) with transition from drought state to nondrought state in Figures 10a and 10b, and from extreme drought to nonextreme drought (Figures 10c and 10d), representing less frequent drought under water management (cold color) or vice versa (represented by warm color).

3.2.3. Shift of Drought Regimes

To explore how water management may affect drought intensity, we classify hydrological drought into three intensity regimes, that is, moderate, severe, and extreme droughts. The drought classification follows McKee et al. (1993) and Nalbantis and Tsakiris (2009) and is defined based on the SSI value between −1.00 and −1.49 for moderate drought, between −1.50 and −1.99 for severe drought, and less than −2.0, for extreme drought. These drought states occur at the frequency of 9.2%, 4.1%, and 1.9%, respectively, in the historical simulations. SSI values between 0 and −0.99 are considered normal drought, and they occur 34.75% of time in the historical simulation.

Figure 8 shows the empirical cumulative density function (CDF) of the spatial extent for different drought regimes during the irrigation season (JAS). Although the overall impact of water management in JAS is drought relief (Figure 8a), the specific effect varies among the different drought regimes. Figures 8b and 8c show a shift of the CDF by water management toward lower percentage area for both moderate and severe drought regimes, so water management has obvious drought relief effects in these two regimes. However, for extreme drought, the spatial extent expands with water management (Figure 8d). This phenomenon can be explained by the regional CDF changes (Figure 9). Water management reduces the spatial extent for all drought regimes in regions with low water demand (Midwest, Northeast, and Southeast), but it produces a mix of drought intensification and alleviation effect in regions with intense water demand (Northwest, Southwest, and the Great Plains). Note that both local extraction and reservoir regulation can have an impact on streamflow in areas downstream of reservoirs. During the summer irrigation season, reservoir regulation has a dominating drought alleviation effect for moderate and severe droughts. However, when water demand is intense, the drought intensifying effect of local extraction can dominate over the alleviating effect of reservoir regulation on extreme drought, even for areas downstream of reservoirs.

Figure 10 shows the spatial distributions of water management induced drought changes over the reservoir affected grid cells in the future period of 2060–2095. The changes in drought at each grid are expressed in terms of the fraction of years with a shift from nondrought regime to drought regime (or nonextreme drought regime to extreme drought regime), or vice versa. The spatial patterns for RCP4.5 are very similar to those of RCP8.5, despite the pronounced difference in warming and precipitation changes between the two scenarios. Generally, the drought alleviating effect is more widespread in the eastern U.S., while the drought intensifying effect is more dominant over the western regions with more intense water demand (Figure 3). Areas that exhibit a shift to extreme drought are comparatively small compared to areas with a shift of drought status, that is, most of the reservoir affected grid cells do not experience frequent shift from nonextreme drought to extreme drought or vice versa. Under both RCP4.5 and RCP8.5, water management, mainly local extraction, will lead to increased extreme drought frequency in areas with intense water demand such as California.

4. Conclusion and Discussion

The impacts of water management, including local surface water extraction and reservoir regulation, and climate change on future hydrological drought in the U.S. are investigated using simulations from an integrated modeling framework that considers changes in climate and water demand consistently driven by the socioeconomic and emissions scenarios of RCP4.5 and RCP8.5. Overall, water management intensifies future hydrological drought at the national scale. This substantial drought intensification is mainly driven by local extraction that occurs countrywide. It is nevertheless more acute in the Great Plains and western U.S., where the irrigation water demand is more intense. However, drought is alleviated in areas downstream of reservoirs primarily during the summer irrigation season because of flow enhancement by reservoir regulation. Comparing RCP4.5 and RCP8.5, water management intensifies drought more in RCP4.5 than RCP8.5 because of the increased irrigation water demand to support bioenergy production for emissions mitigation. Focusing only on the irrigation season, reservoir regulation reduces mainly moderate droughts but local extraction increases extreme droughts.

Although the underlying mechanisms of drought discussed in this study are not conceptually sophisticated, few studies have tried to quantify the relative contribution of reservoir regulation and water withdrawal to mitigating or enhancing hydrological drought for the 21st century. A few studies have looked at the human water management on hydrological drought (He et al., 2017; Wanders & Wada, 2015) but have not separated the effect of reservoir from water use, mainly due to the limitation of modeling resolution and stationary water demand assumption. We show that human activities tend to increasingly intensify future hydrological drought in United States. Nevertheless, for areas downstream of reservoirs, water management alleviates rather than increases drought, particularly in the irrigation season. We note that over some regions such as Midwest, Northeast, and Southeast, the net effects of climate mitigation (i.e., difference between RCP4.5 and 8.5) could dominate over those of water management. However, this finding is based on the assumption of static infrastructure, that is, no construction of new reservoirs in the future.

This study used regional climate change simulations produced by a single climate model. As shown by the CMIP5 multimodel ensemble, large uncertainty exists in climate model projections of future changes, particularly for variables related to water. For example, Deser et al. (2012), and Hawkins and Sutton (2009), and Hawkins and Sutton (2009) illustrated the significant uncertainty in projecting future changes at local and regional scales due to internal variability, and uncertainty associated with climate model differences can also be significant in the midcentury (Hawkins & Sutton 2009). However, uncertainty in the climate change projections may not affect the robustness of our conclusions regarding the impacts of water management on hydrological drought, because the impacts are almost constant in time and rather insensitive to the scenarios. Moreover, the mean seasonal and spatial patterns of wet/dry trends from our model are generally consistent with the multimodel ensemble from CMIP5 (Gao et al., 2014; Hejazi et al., 2015). Nevertheless, uncertainty in the climate change projections affects our ability to evaluate the impacts of climate change and emissions mitigation on hydrological drought and should be quantified in future studies. Although the water management model was evaluated in previous efforts (Voisin, Li, et al., 2013; Voisin, Liu, et al., 2013), some modeling uncertainties may have important effects on our simulations and analyses particularly over areas that are subject to the impacts of reservoir operations. For example, the WM model does not represent deep groundwater supply and transbasin diversions. Instead, it assumes an unlimited groundwater supply so even during drought years, there is a reliable water supply to alleviate flow deficit downstream of the reservoirs. This is not always unrealistic except in areas with no groundwater pumping infrastructures. Sensitivity of our results to various sources of uncertainties in our modeling framework should be investigated in the future.

Despite some limitations, our results indicate significant water management impacts on hydrological drought that are relatively consistent over time and the magnitude can be as large as the difference between the RCP4.5 and RCP8.5 scenarios. This motivates a need to include human activities in combination with climate change in evaluating hydrological drought changes in the future. Furthermore, as drought is intensified more in an emissions mitigation scenario with increased irrigation demand for bioenergy production compared to the business-as-usual scenario at the national level, the impacts of emissions mitigation must be evaluated by considering its benefit in reducing warming and evapotranspiration against its effects on increasing water demand and intensifying drought.

As the growing acute water scarcity has posed profound challenges for the human water consumption (e.g., western USA), soft strategies have been recommended to achieve water sustainability (Gober & Kirkwood, 2010; Macdonald, 2010), besides the water management through reservoirs. The water saving approach using soft strategies can help to mitigate hydrological drought. Several soft strategies are commonly used in urban areas, such as reduction in water demand, water pricing policies, and tactical shorter-term actions that are usually implemented during a drought, such as water use restrictions. It is also possible to reduce water demands by increasing the efficiency of water used and reuse in the regional system, by changing to salt and/or drought tolerant crops, and/or by decreasing agriculture or moving it to areas with more appropriate environmental conditions. More studies are needed to explore different strategies to address potential water scarcity in the future.

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