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Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming

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Abstract

Despite the importance of surface water to people and ecosystems, few studies have explored detectable changes in surface water supply in a changing climate, given its large natural variability. Here we analyze runoff projections from the Variable Infiltration Capacity hydrological model driven by 97 downscaled and bias-corrected Coupled Model Intercomparison Project Phase 5 climate projections over the conterminous United States (CONUS). Our results show that more than 40% of the CONUS land area will experience significant changes in the probability distribution functions (i.e. PDFs) of summer and winter runoff by the end of the 21st century, which may pose great challenges to future surface water supply. Sub-basin mean runoff PDFs are projected to change significantly after 2040s depending on the emission scenarios, with earliest occurrence in the Pacific Northwest and northern California regions. When examining the response as a function of changes in the global mean temperature (ΔGMT), a linear relationship is revealed at the 95% confidence level. Generally, 1 °C increase of GMT leads to 11% and 17% more lands experiencing changes in summer and winter runoff PDFs, respectively. Such changes in land fraction scale with ΔGMT at the country scale independent of emission scenarios, but the same relationship does not necessarily hold at sub-basin scales, due to the larger role of atmospheric circulation changes and their uncertainties on regional precipitation. Further analyses show that the emergence of significant changes in sub-basin runoff PDFs is indicative of the emergence of new hydrology regimes and it is dominated by the changes in variability rather than shift in the mean, regardless of the emission scenarios.

1. Introduction

Global warming is increasing the frequency and severity of extreme hydrological events such as floods and droughts around the world (Lehner *et al* 2006, Dai 2013, Hirabayashi *et al* 2013, Dankers *et al* 2014, Leng *et al* 2015a). The increasing frequency of extreme hydrological events leaves an open question as to how the changes in hydrology have evolved or when they will emerge from the internal variability. In terms of impacts, changes in hydrology become most relevant when a novel hydrologic regime emerges, and detecting the emergence of such changes from a baseline period has great implications for designing adaptation and mitigation strategies.

Previous studies defined the 'time of emergence' as the point in time when observations or model simulations show changes from a given baseline period above natural variability. These efforts mainly focused on climatic variables such as mean temperature and precipitation (Battisti and Naylor 2009, Diffenbaugh and Scherer 2011, Mahlstein *et al* 2011, Hansen *et al* 2012), extreme temperature and precipitation (Maraun 2013, Scherer and Diffenbaugh 2014), and snow, temperature and timing of streamflow (Barnett *et al* 2008). Despite the importance of surface water to people, few

have investigated the emergence of significant changes in surface water supply in a changing climate. In addition, previous studies have often used model-based signal-to-noise ratios (Hawkins and Sutton 2012), ratios of standard deviations (std) to mean climatology (Hansen *et al* 2012), or exceedances of a median value (Diffenbaugh and Scherer 2011) to determine the time of emergence. These studies did not take into account the changes in probability distributions of variables of interest (including mean, variability, skewness or other high order moments), which would challenge water management practices more than changes in a single statistical moment of the distributions. Investigating the emergence of significant changes in surface water distributions from those seen in the baseline period (i.e. emergence of new hydrology regime) would provide more insights for climate adaptation strategies.

The ongoing policy debates among governments and organizations focus more on limiting the global mean temperature rise (ΔGMT) to a target value to avoid dangerous impacts (Meinshausen *et al* 2009, Smith *et al* 2009, Joshi *et al* 2011). However, the general public has not yet fully comprehended the regional impacts associated with a certain global warming target. In other words, there is a need to effectively translate changes in global mean temperature to the societal and environmental consequences at regional scale. A quantitative understanding of the regional impacts in response to a specific global warming target can inform policy-makers and local stakeholders for designing better adaptation strategies. In this study, we investigate future changes in surface water supply and demonstrate the feasibility of quantitatively relating global temperature changes to regional hydrologic changes in the conterminous United States (CONUS) at two spatial scales—the country scale and the sub-basin scale. Specifically, we examine the following questions: (1) When will changes in runoff, in terms of its PDFs and statistical moments, emerge significantly from the baseline period (i.e., emergence of new hydrology regimes)? What are the similarity and difference between the response of runoff and precipitation distributions to global warming? (2) Are there robust scaling relations between ΔGMT and the emergent hydrologic regimes at different spatial scales? (3) Which aspects of the probability distribution changes (i.e., mean, variability, or higher order moments) lead to the emergences?

2. Data and methodology

2.1. Hydro-climate projections

We used climate projections from 31 models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al* 2012) in this study. The CMIP5 models represent notable changes compared to the CMIP3 models in terms of the higher spatial resolutions, updated model physics, and new greenhouse gas (GHG) emissions and land use land cover change (LULCC) scenarios. We used the future projections under four Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). In these GHG emissions and LULCC scenarios, anthropogenic radiative forcing is capped below 2.6, 4.5, 6.0 and 8.5 $W\,m^{-2}$, respectively, throughout the 21st century (Moss *et al* 2010). The CMIP5 climate projections were statistically downscaled to 1/8 degree resolution and bias-corrected based on the observed climate (Maurer *et al* 2002) over CONUS using the bias-correction and spatial-downscaling approach (BCSD) (Wood *et al* 2004) The CMIP5 BCSD climate has the same monthly climatology as the observed climate in the overlapping period of 1950–1999 (Reclamation 2013). The CMIP5 hydrological projections (Reclamation 2014) were simulated by the Variable Infiltration Capacity (VIC) model (Liang *et al* 1994, 1996) driven by the CMIP5 BCSD climate (Reclamation 2013) and archived at ftp://gdo-dcp.ucllnl.org/pub/dcp/archive/cmip5/hydro. The VIC model is a macroscale hydrologic model that solves the water balance at each model grid cell with representation of subgrid-scale variability (Liang *et al* 1994) and has been widely used in assessing climate change impacts on hydrology (Wood *et al* 2004, Christensen and Lettenmaier 2007, Maurer 2007, Vano and Lettenmaier 2014, Leng *et al* 2015a, 2015d). A total of 97 hydrologic projections over CONUS driven by the CMIP5 BCSD projections are used in this study (table S1). These projections have been evaluated (Wood and Mizukami 2014) and a high level of consistency is found in terms of the seasonal mean and variability compared with the historical VIC simulations, which were calibrated against observations (see supplementary materials).

2.2. Detecting the emergence of significant changes in surface water distributions

Here, the two-sample Kolmogorov–Smirnov (KS) test (Chakravarti *et al* 1967) is used to quantitatively compare the probability distribution functions (PDFs) of the historical and future time series. The KS test returns a decision of true/false for the null hypothesis that two time series are sampled from the same PDF. The statistics is nonparametric and makes no assumptions about the distribution itself, so it has been widely used in hydro-climatic studies (Mahlstein *et al* 2011, Russo and Sterl 2012, Runge *et al* 2016, Schaller *et al* 2016). The KS test is calculated as follows:

$$F_m(x) = \frac{1}{m}\sum_{i=1}^{m} I(X_i \leqslant X), \tag{1}$$

$$H_n(x) = \frac{1}{n}\sum_{i=1}^{n} I(X_i \leqslant X), \tag{2}$$

where $F_m(x)$ and $H_n(x)$ are the empirical PDFs of the future and historical time series of variable x,

respectively (Van der Vaart 2000), i is the time step of the time series, m and n are the sample sizes of the two time series, respectively. I is the indicator function, which equals 1 if $X_i \leqslant x$ and 0 otherwise.

The distance between the empirical PDFs of the two samples ($D_{m,n}$) is calculated as follows:

$$D_{m,n} = \sup_x |F_m(x) - H_n(x)|, \quad (3)$$

where sup is the supremum function for measuring the least upper bound of the distances between $F_m(x)$ and $H_n(x)$. The null hypothesis of the KS statistics is that the samples are drawn from the same distribution, which is rejected at a confidence level a (set to be 95% in this study).

$$D_{m,n} > i(a)\sqrt{\frac{m+n}{m \times n}}, \quad (4)$$

where $i(a)$ is the inverse of the Kolmogorov distribution at a. Values of D closer to zero indicate that the future distribution is similar to that in the history. Conversely, larger D values indicate the distributions differ from each other. In this study, a significant change is defined when the value of the KS test statistics D is equal to 1.

2.3. Decomposition of the detected changes in distributions

Statistically, changes in the distribution can be attributed to many aspects including the mean, variance, skewness, or other higher order moments. In order to quantify the respective contributions from these factors to changes in the distributions, pseudo scenarios are constructed based on statistical transformation of the historical simulations. The first pseudo scenario $V'_{f,i}$ is generated by scaling the historical simulations with the ratios between the means of the future and historical simulations.

$$V'_{f,i} = V_{h,i} * r_{\text{ave}}, \quad i = 1, \ 2 \ldots n, \quad (5)$$

where $V_{h,i}$ denotes the time series of historical simulations, h denotes the historical time period, i is the time step with length up to n, r_{ave} is the ratio between the means of the future and historical simulations as follows:

$$r_{\text{ave}} = \sum_{i=1}^{n} V_{f,i} \Big/ \sum_{i=1}^{n} V_{h,i}, \quad (6)$$

where $V_{f,i}$ denotes the future simulations, f denotes the future time period. The distribution of the transformed time series (i.e., $V'_{f,i}$) has the same shape as that of the historical simulations but with the mean shifted to that of the future simulations. The pseudo scenario is then compared with the historical simulations through the KS test.

$$S_1 = \text{KS}(V'_{f,i}, V_{h,i}). \quad (7)$$

If $S_1 = 1$, changes in the mean contribute to the detected changes in PDF since only the mean is altered with other statistical moments remaining the same as those of the raw historical simulations. Otherwise, the second pseudo scenario $V''_{f,i}$ is constructed by scaling the anomalies of historical simulations with the ratio between the std of the future simulations to that of the historical simulations as follows:

$$V''_{f,i} = V_{a,h,i} * r_{\text{std}}, \quad i = 1, \ 2 \ldots n, \quad (8)$$

where $V_{a,h,i}$ is the anomaly of historical simulation (with respect to its long-term mean), r_{std} is the ratio of the std of historical simulations to that of future simulations.

$$r_{\text{std}} = \text{STD}(V_{f,i})/\text{STD}(V_{h,i}). \quad (9)$$

The transformed time series has the same mean as the historical simulations but with its variability (i.e., std, referred to as std hereafter) changed to be the same as that of the future simulations. The pseudo scenario ($V''_{f,i}$) is then compared with the historical simulations through the KS test as:

$$S_2 = \text{KS}(V''_{f,i}, V_{h,i}). \quad (10)$$

If $S_2 = =1$, changes in variability contribute to the detected changes in PDFs. Otherwise, the third pseudo scenario $V'''_{f,i}$ is constructed by scaling both the mean and variability of historical simulations as follows:

$$V'''_{f,i} = V_{a,h,i} * r_{\text{std}} + \sum_{i=1}^{n} V_{f,i} \Big/ n \quad (11)$$

so that the transformed time series has the same mean and std as that of the future simulations with other statistical moments being the same as those of the historical simulations. The third pseudo scenario is then compared with the historical simulations through the KS test as:

$$S_3 = \text{KS}(V'''_{f,i}, V_{h,i}). \quad (12)$$

If $S_3 = =1$, changes in both mean and variability contribute to the detected distribution changes. Otherwise, changes in the distribution are due to changes in the skewness and/or other higher order moments.

2.4. Analysis

We applied the KS test to the period 1970–2099 for the 97 hydrological projections under the four emission scenarios. For a given 30 yr time window, we counted the fraction of grids within each spatial domain (e.g., country, sub-basin) with significant changes in distributions as detected by the KS test. The emergence of significant changes is defined as the time when the future distribution differs significantly from the baseline period, and the distributions in all subsequent 30 yr periods also differ significantly from the baseline period. We then constructed the relations between ΔGMT and the land fraction experiencing such changes. The sensitivity of land fractions experiencing significant changes in distributions to ΔGMT was tested at the 95% confidence level. ΔGMT was calculated as the difference between the 30 year global mean annual temperatures between the future and the baseline periods. Based on the pseudo scenarios generated, we attributed the future emergence of

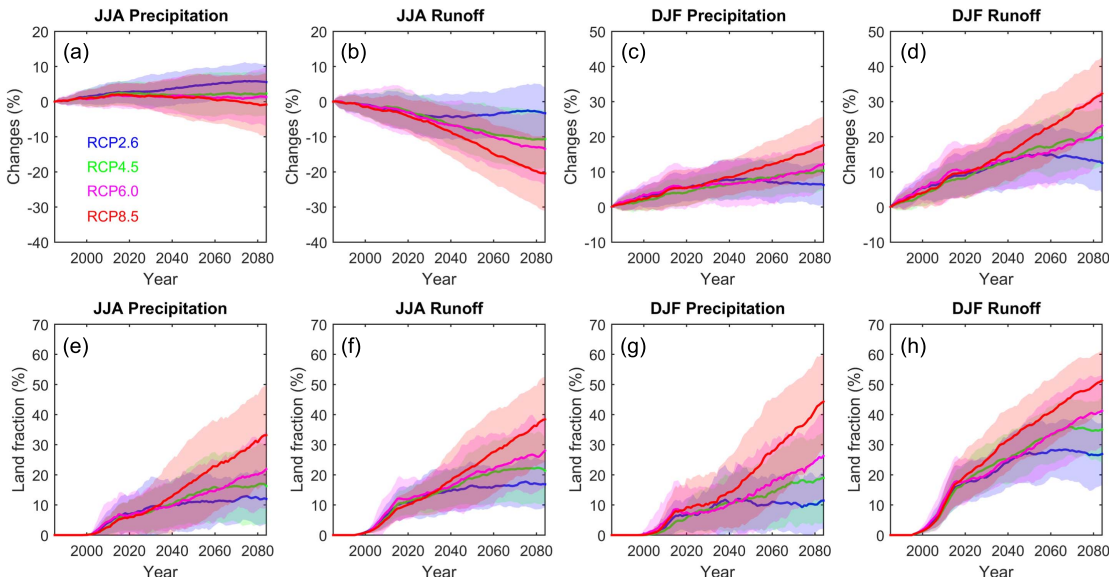

Figure 1. Changes (%) in US mean of summer (June–July–August, JJA) and winter (December–January–February, DJF) precipitation and runoff (top panel) and changes in the fraction (%) of US's land experiencing significant changes in seasonal precipitation and runoff distributions (bottom panel) relative to 1970–1999 period under four Representative Concentrations Pathway (RCP) scenarios. The year denotes the 30 yr period centered at that year. Solid lines indicate the multi-model ensemble mean. Shaded areas denoted one standard deviation for characterizing the inter-model spread.

significant changes in distributions to changes in the mean, variability or other higher order moments (see section 2.3). The accompanying changes in extreme events were calculated to represent the extreme event changes at the time of such emergencies.

We focus on the summer (June–July–August, JJA) and winter (December–January–February, DJF) seasons. Basin-average projections are investigated at the 4-digit Hydrologic Unit Code (HUC4) spatial units (http://water.usgs.gov/GIS/huc.html) to reduce spatial noise. In addition, calibrations of the UW_VIC dataset used in our validations were mostly conducted at the HUC4 level, thus giving us greater confidence at this spatial scale. Instead of using the preindustrial era as the baseline period, global warming is defined here as the global mean temperature changes relative to 1970–1999 as baseline. Given that the global mean temperature has increased by about 0.8 °C since the pre-industrial era by the end of the 20th century (Hansen *et al* 2006), readers can simply subtract our estimates by 0.8 °C if changes relative to the pre-industrial era are preferred. We acknowledge that the magnitude of changes may differ if a different baseline period was selected. Our calculations are performed for each model and the multi-model ensemble mean is used for analysis (Pierce *et al* 2009, Schwalm *et al* 2015, Leng *et al* 2015b). The inter-model std is used to characterize the model spread. Model agreement is used to indicate the robustness of the changes. Here, if two thirds of the models agree on the sign of changes, the changes are considered robust, which coincides with the standard used by IPCC in its probabilistic statements to signify a likely outcome (Mastrandrea *et al* 2010).

3. Results

3.1. Significant changes in seasonal surface water distributions during the 21st century

The country-mean DJF precipitation are projected to increase in the 21st century across all four scenarios except for the periods after 2040s under RCP2.6 when GHG concentrations reach a maximum and begin to decrease. However, little change is found for JJA precipitation (figures 1(a)–(d)). Increases in DJF precipitation are progressively larger from the lower emissions (RCP2.6) to the higher emissions scenarios (RCP8.5). A similar progression is seen in the DJF runoff, tracking progressively through RCPs 2.6, 4.5, 6.0 and 8.5. Compared to the JJA precipitation, much larger percentage of decrease in JJA runoff is found due to enhanced evaporative demand in response to the increasing temperature (Milly *et al* 2005). In contrast, DJF runoff is projected to increase much faster than the corresponding precipitation, due to a higher fraction of precipitation falling as rain instead of snow (Leung *et al* 2004, Barnett *et al* 2005, Hidalgo *et al* 2009, Das *et al* 2011). These seasonal changes are more significant than the changes in annual runoff, demonstrating the amplified seasonality of runoff (figure S3). Notably, the uncertainty ranges for runoff changes are much larger than precipitation for both JJA and DJF, indicating the amplification of uncertainties from precipitation to surface hydrologic processes.

In addition to the changes in long-term mean conditions of water resources, changes in the distribution (i.e. PDFs) would be especially important for local water resource management and adaptation strategies

since shifts in the mean and/or variability of distribution indicate changing probability of extreme events. Figures 1(e)–(h) shows the changes in land fraction of CONUS experiencing significant changes in seasonal precipitation and runoff (as detected by the KS test) in the 21st century relative to 1970–1999. Generally, land fraction experiencing significant changes in runoff distribution is larger than that of precipitation in any given time window. The fraction of lands experiencing significant changes in JJA runoff distribution tends to increase especially after the 2040s and peak at the end of the 21st century under all emission scenarios except for RCP2.6 after the 2050s (figure 1(f)). By the end of the 21st century, about 40% of US land is projected to experience significant changes in the JJA runoff distributions under RCP8.5 while the largest increase for RCP6.0, RCP4.5 and RCP2.6 is 28%, 21% and 18% respectively, potentially posing challenges to future surface water supply. Compared to JJA, land grids experiencing significant changes in DJF runoff distribution are projected to increase at a much faster rate and 50%, 40%, 35% and 27% of US land area will experience such significant changes by the end of the 21st century, for the four RCP scenarios, respectively. Compared to the smaller spread in precipitation changes in the mean, the spread in precipitation distribution changes tend to become larger than that of runoff, suggesting that the spread in the variance of precipitation is potentially larger than that of runoff.

Figure 2 illustrates the spatial pattern of the timing of emergence of significant changes in seasonal runoff (i.e. new hydrology regime) at the HUC4 level. The timing of emergence in JJA runoff is detected around 2050s for a majority of the country with the earliest emergence projected to occur in the coastal Pacific Northwest and northern California currently in the transient hydrologic regime. The spatial patterns of the emergence time is consistent across the four emission scenarios with difference in certain regions such as the Southeast and Upper Mississippi, and less than 30% model spread (relative to the mean) is found in much of the HUC4 basins. The later occurrence of significant changes under RCP2.6 suggests that the proposed mitigation strategies to curtail global warming can delay changes in hydrologic regime locally. Similar patterns are found for DJF runoff with regions of earliest detection generally located in the north and in mountains (e.g., Rockies and Appalachian), suggesting that the snowmelt runoff regime is most sensitive to future warming (Leung *et al* 2004, Stewart *et al* 2005, Barnett *et al* 2008).

3.2. Linkage between global temperature targets and regional surface water changes

When examining the response of CONUS land fraction experiencing significant changes as a function of global mean temperature changes (ΔGMT) in response to GHG emissions and LULCC, a linear relationship at the 95% confidence level is revealed at the country scale (figure 3). Generally, a 1 °C increase of GMT leads to 13.2%, 11.0%, 11.2% and 9.7% more land fractions experiencing changes in JJA runoff. Notably, the sensitivity ranges among emission scenarios (i.e., 1.5%) as a function of ΔGMT is much smaller compared to the sensitivity ranges as a function of time periods (figure 1), demonstrating the effectiveness of using ΔGMT rather than time period as an index to derive impacts. By comparing with the response of the corresponding precipitation, several interesting findings are revealed. For example, the increasing rate of runoff under the same increment of GMT is much larger than the corresponding precipitation changes especially in winter season, indicating that runoff can be used as a better indicator of global warming impacts than precipitation when surface water availability is the indicator of interest. Importantly, it is found that land fractions experiencing significant JJA and DJF precipitation changes scale linearly with ΔGMT; the scaling is independent of emission scenarios, with an uncertainty range (normalized by the mean) of 5.8% and 9.0%, respectively. These findings are consistent with previous studies showing robust scaling relations between global warming and global climate mean and extreme impacts (Tebaldi and Arblaster 2014, Pendergrass *et al* 2015, Seneviratne *et al* 2016). However, the uncertainty in deriving the impacts on seasonal runoff with a given ΔGMT becomes larger (JJA, 13.12%, DJF, 20.9%) compared to precipitation, reflecting the more variable runoff conditions compared to precipitation.

Spatially, JJA runoff responds more sensitively than precipitation to global warming for all river basins across the US with the largest changes projected in Pacific Northwest and Upper Colorado basins corresponding to changes in the snowmelt regime (figure 4). As for the winter season, similar spatial structures of precipitation and runoff responses are found, but with much larger sensitivities. The larger sensitivities in winter runoff may arise from changes in the phase of precipitation from snow to rain in a warmer climate (the sensitivity in precipitation amount is much lower), thus contributing more directly to runoff in winter. In extreme cases, more than 30% of lands in river basins over the northwestern US will experience such significant change in runoff distributions for each 1 °C GMT increase.

We further examine the scaling relations at the HUC4 river basin scale to determine if similar relations hold at finer resolutions. Figure 5 shows the HUC4 level uncertainties (%) in the derived relations between ΔGMT and land fraction experiencing significant changes in seasonal precipitation and runoff distributions. It is found that large uncertainties exist when using ΔGMT to derive the land fraction experiencing significant changes in both seasonal precipitation and runoff PDFs at the HUC4 level. In extreme cases, the uncertainty levels in some basins can be up

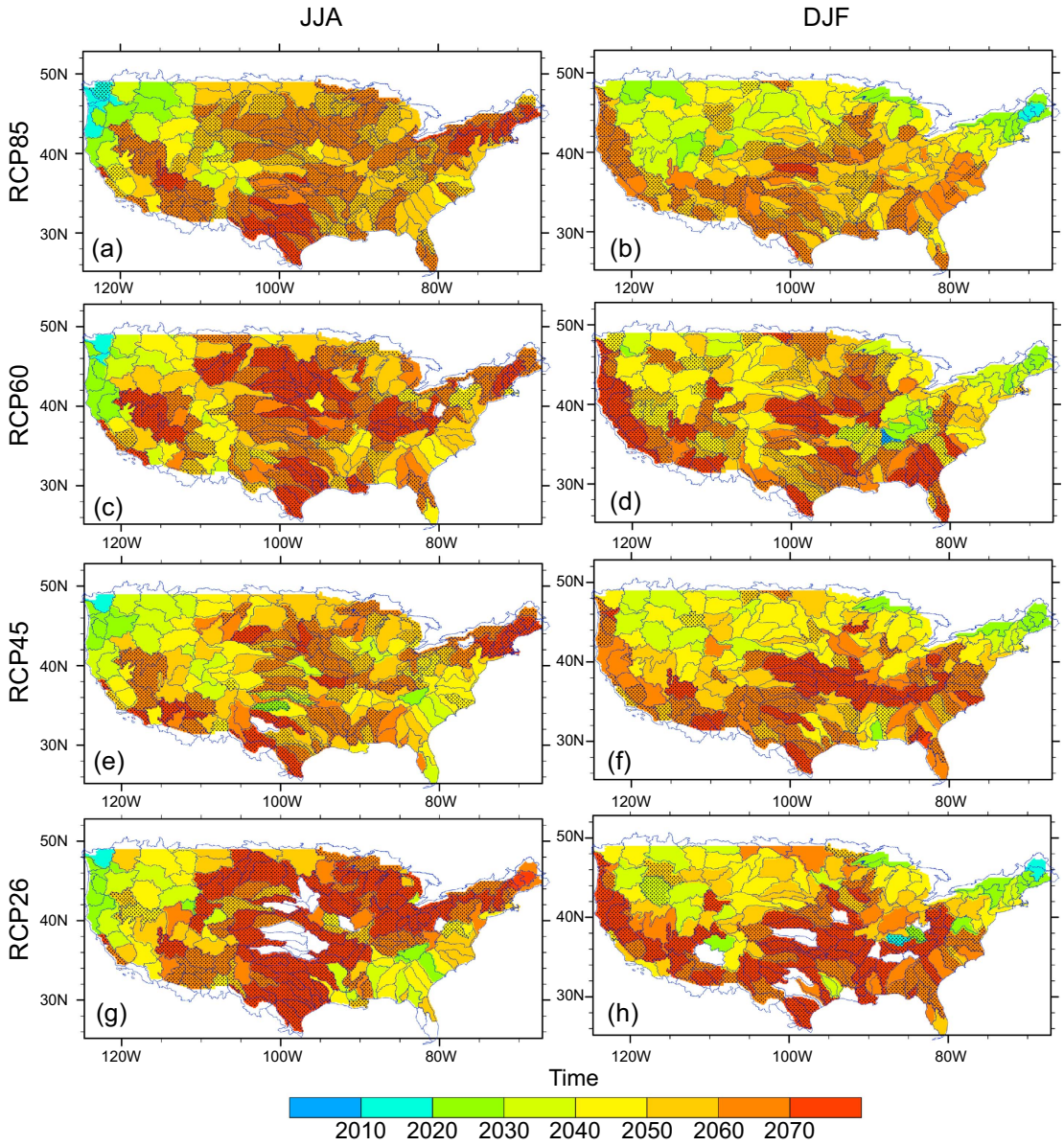

Figure 2. Time of emergence for significant changes in basin mean summer (June–July–August, JJA) and winter (December–January–February, DJF) runoff distributions at the HUC4 basin level. The time denotes the 30 yr period centered at that year when runoff distributions differ significantly in and after that period relative to 1970–1999 period. The basins experiencing no significant distribution changes during 21st century are masked out as blank. Multi-model ensemble means are shown for each RCP scenario while dots indicate the areas where the inter-model range is less than 30% of the mean.

to 70% (figure 5(a)). More than 70% of the HUC4 basins in CONUS are prone to uncertainties larger than that at the country level (figure 5(b)). Instead of the larger uncertainty in runoff than precipitation at the country level for both seasons, 27% of the basins will have larger uncertainty in precipitation than runoff in winter. Overall, our results suggest that the simple linear relation between ΔGMT and surface water changes does not hold at local scales, so the scaling relations are scale-dependent.

3.3. Statistical decomposition of the significant changes in surface water distributions

By decomposing the significant changes in seasonal runoff distributions into changes of mean, std or skewness/higher order moments, the contributions of each factor to the emergence are quantified. Results show that such emergence is explained largely by the changes in the interannual variability, while changes in the mean are responsible in very limited sub-basins in the Southwest and Great Plains (figure 6). Importantly, the contribution of changes in variability is robust across the four emission scenarios, with more than two thirds of the models agreeing on the ensemble results in most sub-basins across CONUS. For precipitation, the distribution changes are even more dominated by changes in variability, implying that the increase in variability in runoff is mainly driven by the increase in variability of precipitation. Our results demonstrate that the US seasonal basin-mean surface

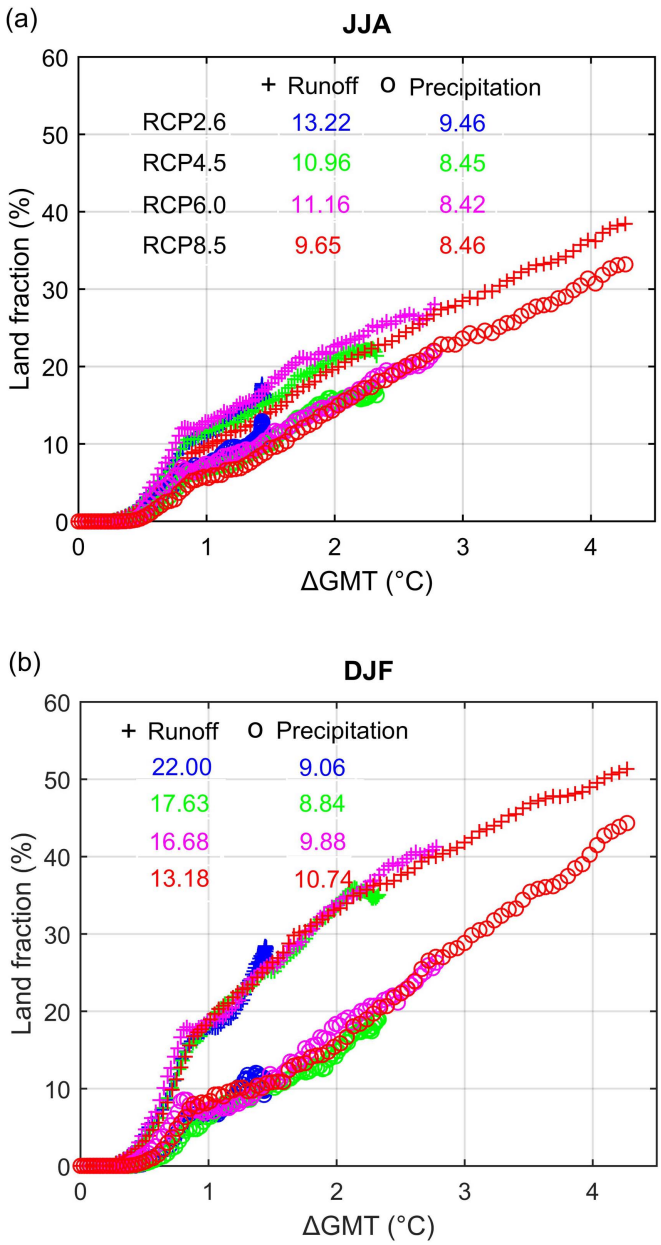

Figure 3. Changes in the fraction (%) of US's land area experiencing significant changes in summer (June–July–August, JJA) and winter (December–January–February, DJF) precipitation and runoff distributions as a function of GMT increments (ΔGMT). Multi-model ensemble means under the RCPs are shown. Values indicate the land fraction increases per 1 °C GMT increase under each emission scenario. The linear relations are tested with student-t test and are significant at the 95% confidence level.

water might experience a pronounced increase in year-to-year variability in response to GHG forcing. Such increase in variability can lead to the emergence of new hydrologic regimes.

Indeed, JJA low flows (5th percentile) accompanying the emergence are projected to decrease over a significant portion of the US, especially in the Northwestern US, by more than 30%, while increases are projected in limited regions by ~5% over Southeastern regions (figure 7). In contrast, DJF low flows are projected to increase over much of the US, with decrease limited to Arkansas-White-Red and Texas-Gulf basins (figure S4). The spatial pattern of changes in high flow (95th percentile) is similar to that of low flows with largest decrease of JJA high flows in southern Rockies, California and Rio Grande Basins. Compared to those in JJA, the magnitudes of increase in DJF high flows are much larger and could exceed 40% in many basins. These changes would strongly affect the incidence of floods and droughts in the future and potentially represent a serious challenge to adaptive response strategies designed to cope with climate change.

4. Uncertainty and limitations

By comparing with the historical VIC simulations, which were calibrated against observations, a high level of consistency is found in the CMIP5 BCSD

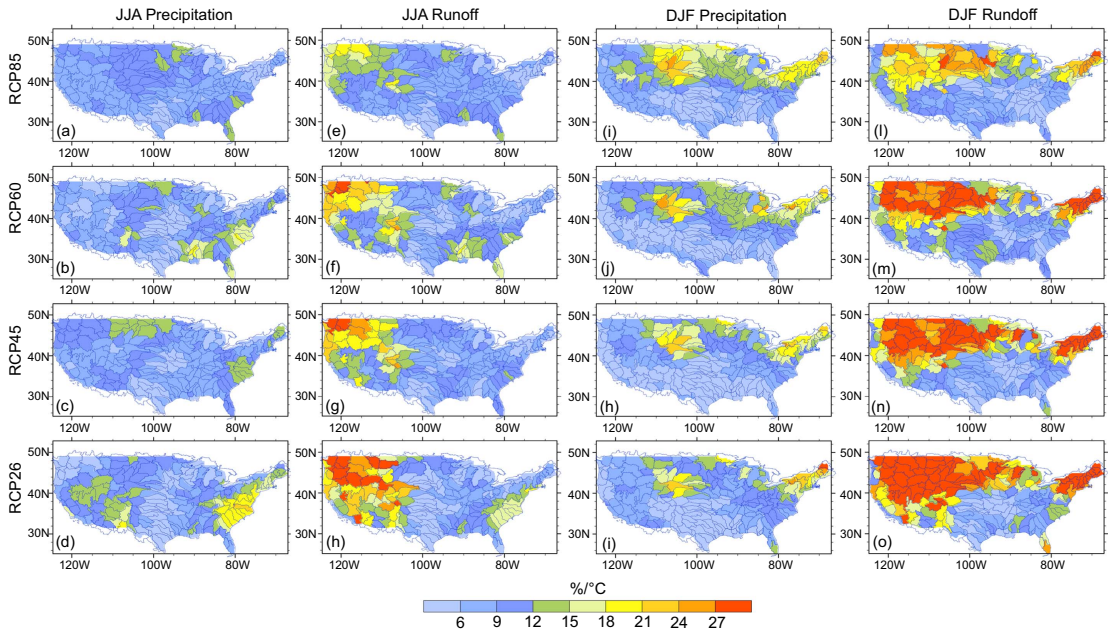

Figure 4. Sensitivity of the land area fraction (%) in each HUC4 basin experiencing significant changes in summer (June–July–August, JJA) and winter (December–January–February, DJF) precipitation and runoff distributions in response to 1 °C GMT increase. Multi-model ensemble means under the RCPs are shown. The linear relations are tested with student-t test and are significant at the 95% confidence level.

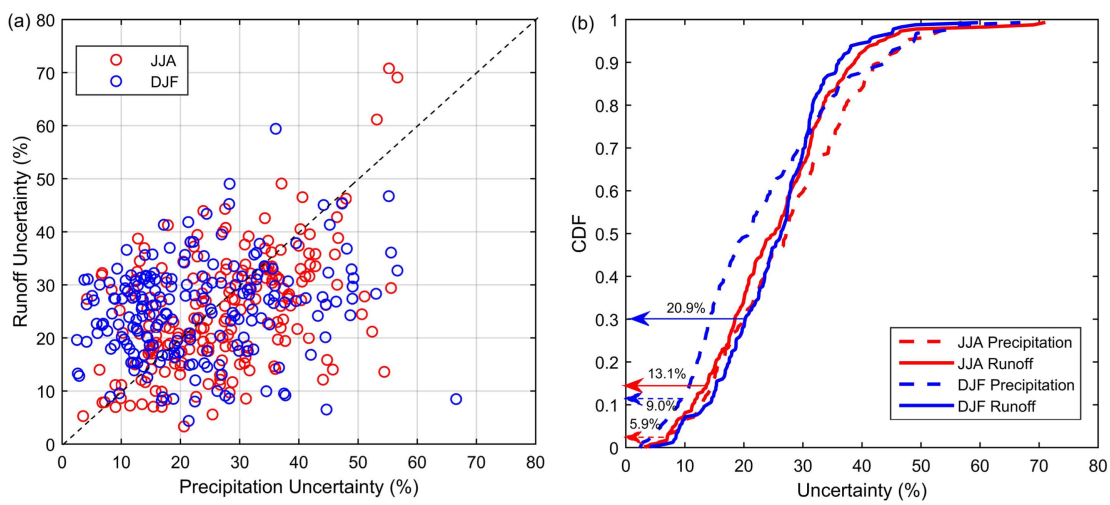

Figure 5. Uncertainties (%) in using global temperature increments (ΔGMT) to derive the land fraction experiencing significant changes in summer (June–July–August, JJA) and winter (December–January–February, DJF) precipitation and runoff distributions. Uncertainties are defined as the percentage of standard deviations of the derived relations among the four emission scenarios normalized by the mean: (a) the uncertainties of precipitation versus runoff. Each dot represents a HUC4 basin, (b) the cumulative distribution function (CDF) of the uncertainties for all HUC4 basins. Horizontal arrows indicate the percentage of HUC4 basins with uncertainty equal to or lower than that at the country level (as shown by the number).

hydrological projections in terms of the seasonal mean and variability (see supplementary materials). However, models that underestimate inter-annual variability tend to show larger exceedance rates and vice versa. In some regions such as the Pacific Northwest where the CMIP5 BCSD climate produce relatively higher variability, the estimates for the timing of emergence may be slightly conservative (figures S1 and S2).

Besides model biases, there are some limitations to our general conclusions, because certain factors that affect runoff are not considered in our study. For example, although the CMIP5 climate models include LULCC following the RCP scenarios, offline simulations by VIC ignore the LULCC so changes in runoff related to land use and land cover are not represented. Hence this study analyzes only the natural runoff response to climate changes, although watershed

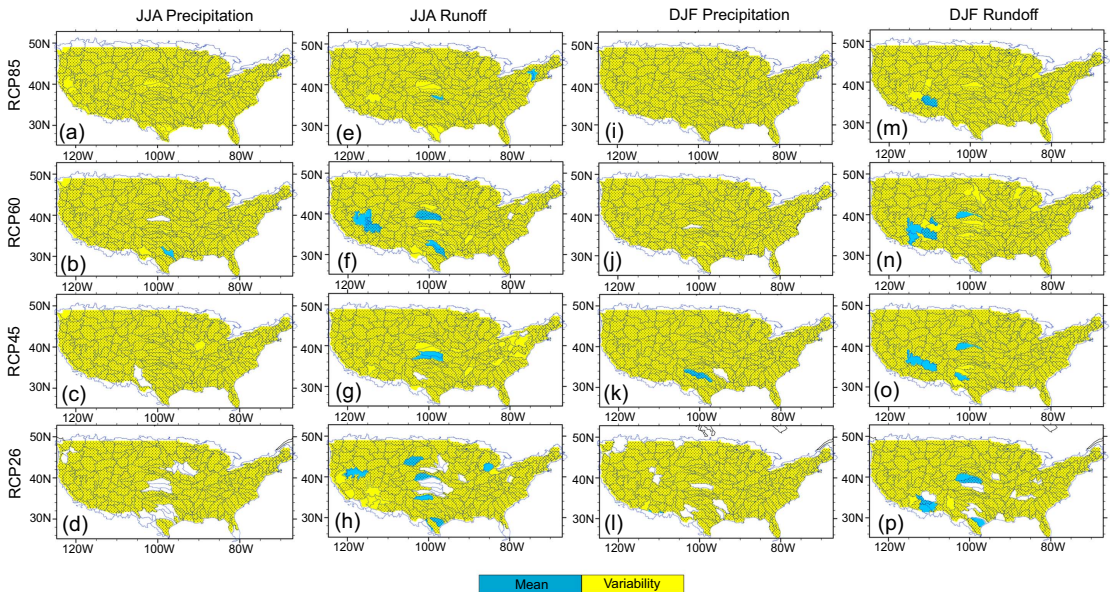

Figure 6. Statistical decomposition of emergence of significant changes in basin-mean summer (June–July–August, JJA) and winter (December–January–February, DJF) precipitation and runoff distributions to changes in mean or variability at the HUC4 level. Those basins experiencing no significant distribution changes during the 21st century are masked out as blank. Decompositions are done for each model and the most likely result from the ensemble of each RCP scenario are shown with dots indicating the areas where more than two thirds of the models agree on the decomposition results.

characteristics are projected to change under global warming and socio-economic changes and could affect runoff by affecting biophysical properties such as vegetation dynamics (Gedney *et al* 2006, Betts *et al* 2007, Shi *et al* 2011, Lei *et al* 2014). The VIC hydrology lacks a representation of groundwater and surface water interactions (Maxwell *et al* 2007, Leung *et al* 2011, Taylor *et al* 2013) so the potential effects of groundwater in regulating surface hydrological variability are not captured in our analysis. In addition to the natural hydrological processes, human influence has been identified to be important in regional hydrology through water withdrawals (Döll *et al* 2012, Leng *et al* 2013, 2014) and land use changes (Piao *et al* 2007). Leng *et al* (2015c) found that irrigation water use can further exacerbate low-flow conditions in some watersheds relying extensively on irrigation, especially in a warmer climate. The extent to which these local factors interact with global warming and disturb the basin-level long-term mean and variability of seasonal runoff remains unclear and requires more explicit and comprehensive coupled modeling studies in the future. Hence, our results should mainly represent the first-order impacts of global warming on regional surface water.

In addition to uncertainties associated with the hydro-climatic dataset used, we acknowledge that there are limitations in the analyzing approach. First, the period 1970–1999 was chosen as the reference period for detection of the emergence of new hydrological regimes. However, the period 1970–1999 may already include an anthropogenic signal that surpasses natural climate variability, as shown in Barnett *et al* (2008). In other words, our results may indicate the emergence of yet another regime with respect to 1970–1999. Hence, our results are dependent on the reference period chosen for analyses. Second, the emergence of new hydrological regimes is linked to global temperature changes to quantify regional impacts associated with a certain global warming target. Given the simple relationship between CO_2 emissions and global warming targets as documented in existing literature (Allen *et al* 2009, Meinshausen *et al* 2009, Friedlingstein *et al* 2014, Knutti and Rogelj 2015, Seneviratne *et al* 2016), we were able to associate global warming targets to regional hydrologic impacts to better inform the general public and policy-makers. However, it should be acknowledged that GHG emissions are the real forcing variables driving changes in both global temperature and regional hydrology. In addition, cautions need to be taken because such relations shall not be treated as causality and linearity, due to uncertainties in climate projections, downscaling algorithms, impact models, and time varying land surface conditions. Third, when the emergence of a new hydrological regime is detected, we then construct several pseudo scenarios to explore whether such an emergence can be attributed to changes in mean, variability or skewness in the PDF. In each pseudo scenario, a specific statistical moment of the historical climate is adjusted to be the same as that of the future climate while other statistical moments are kept unchanged. We only consider four categories: changes in the mean or variability or both, or higher order moments, without considering other factors that could be potentially important. For example, a non-significant change in variability and a non-

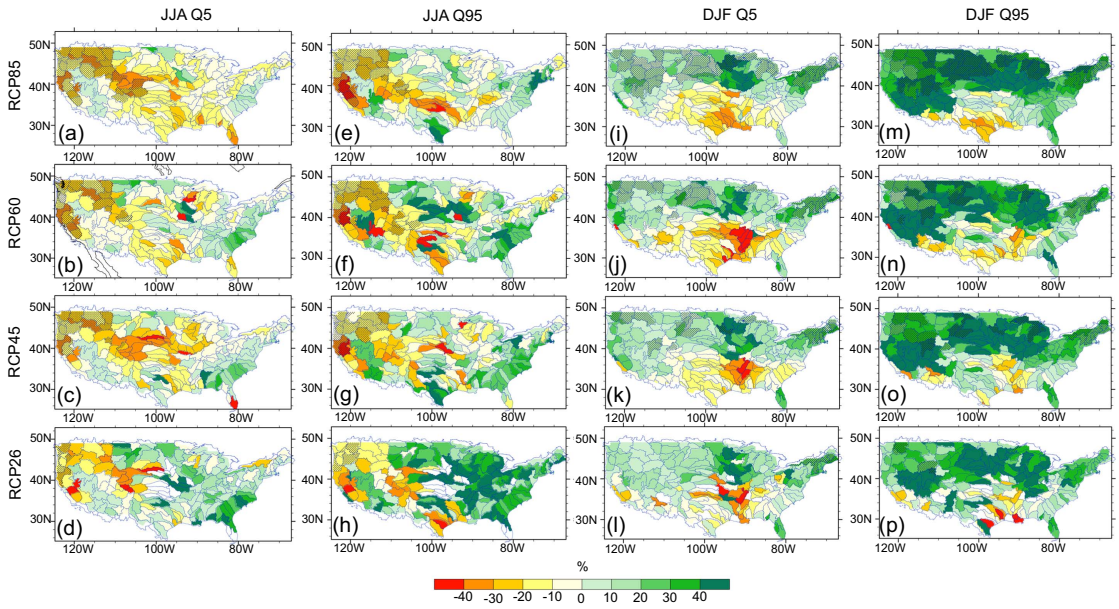

Figure 7. Changes (%) in the low flows (Q5) and high flows (Q95) of basin-mean summer (June–July–August, JJA) and winter (December–January–February, DJF) runoff relative to 1970–1999 period under four RCP scenarios at the HUC4 level. The future time period for each basin corresponds to the 30 yr time period when there are significant changes in the distributions. The basins experiencing no significant distribution changes during 21st century are masked out as blank. Multi-model ensemble means are shown for each RCP scenario with dots indicating the areas where more than two thirds of models agree on the change sign.

significant change in mean might still result in a significant change in the distribution, but such a case (if exist) has only been taken into account in the fourth category in a lumped sense.

5. Summary and conclusions

Global warming is affecting the water cycle at both global and regional scales (Huntington 2006). Although global changes in precipitation are well constrained by energy, changes in regional water resources are more variable and have not been clearly quantified, especially when the probability density distribution is of concern (including mean, variability, skewness or other higher orders). Indeed, significant changes in the full distributions, indicative of the emergence of new hydrology regimes, could present greater challenges to water management than changes in a single moment of the distribution. In this study, the results from 97 hydro-climate projections (Reclamation 2014) are used to examine the projected changes in surface water resources. We focus on summer and winter seasons since the change in annual mean runoff is generally small compared to that of seasonal runoff (figure S3). In addition to examining the changes as a function of time periods, we link regional surface water changes directly to global warming targets that could be interpreted more easily for informing the general public on the needs for adaptation and mitigation.

Our results suggest that significant changes in the surface water distributions (i.e. PDFs) could be detected at the local to regional scales, pointing to the emergence of new hydrology regimes that could result in great challenges to water resources management across CONUS. Specifically, more than 40% of the country's land will experience significant changes in summer and winter runoff distributions by the end of the 21st century. The smaller magnitude of changes for both summer and winter runoff under RCP2.6 suggest that drastic mitigation strategies against global warming could effectively revert/relieve climate change impacts on local water resources. Overall, the emergences of significant changes in seasonal runoff PDFs are projected to occur after 2040s across the country with their timing depending on emission scenarios. The earliest emergence occurs in the 2030s and is located in the Pacific Northwest and northern California region where water supply is currently dominated by snowmelt runoff. The timing of runoff changes is much earlier than precipitation changes, indicating that runoff is a more effective indicator of global warming than precipitation in regions where future water supply is a concern.

When examining the CONUS response as a function of global mean temperature changes (ΔGMT), a linear relationship is revealed. Generally, a 1 °C increase of GMT leads to 13.2%, 11.0%, 11.2% and 9.7% more land fractions experiencing such changes in summer runoff distributions in the RCP scenarios. These increasing rates with the same increment of GMT are much larger than those corresponding to precipitation, especially in winter. The emergence of significant changes in runoff distribution was attributed to the changes in variability rather than shifts in

the mean across the country, which is robust across the emission scenarios.

This study stands out from previous hydro-climatic impact studies by linking the emergence of new hydrologic regimes directly to global temperature targets, and decomposing such emergence to changes in the mean or variability. Linking global temperature targets to regional consequences would be particularly informative for decision making at the regional scale, both in the context of climate mitigation and adaptation. The range of the increasing rate of land fraction experiencing significant changes in PDFs per degree of global warming among models is small at the national scale, indicating that country-scale surface water distribution changes scale with ΔGMT, independent of emission scenarios with uncertainty range of 13.1% and 20.9% for summer and winter runoff respectively. The scaling relations across the forcing scenarios have great implications for integrated assessment modeling which lack explicit climate and land surface representations. However, the scaling relationship does not hold at the sub-basin scale for most of the country (with uncertainty larger than 30% in 70% of the sub-basins) especially in the winter season when large-scale circulation has more dominant controls on regional precipitation. At larger scales, precipitation changes are dominated by thermodynamical changes associated with warming, while at regional scales, changes in large-scale atmospheric circulation that influence precipitation changes have large uncertainty due to the chaotic nature of atmospheric circulation (Shepherd 2014). Hence, even for large river basins, significant uncertainty is found in projecting changes in precipitation from a large ensemble of simulations by a single model (Deser *et al* 2014). This study highlights the relations between global temperature targets and regional surface water challenges, which could provide more targeted and actionable information for adaptation and mitigation in specific regions of interest.

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