Analysis of U.S. Water Resources under Climate Change

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Elodie Blanc[*†], Kenneth Strzepek[*], Adam Schlosser[*], Henry Jacoby[*], Arthur Gueneau[*‡], Charles Fant[*], Sebastian Rausch[*§], and John Reilly[*]

Abstract

The MIT Integrated Global System Model (IGSM) framework, extended to include a Water Resource System (WRS) component, is applied to an integrated assessment of effects of alternative climate policy scenarios on U.S. water systems. Climate results are downscaled to yield estimates of surface runoff at 99 river basins of the continental U.S., with an exploration of climate patterns that are relatively wet and dry over the region. These estimates are combined with estimated groundwater supplies. An 11-region economic model (USREP) sets conditions driving water requirements estimated for five use sectors, with detailed sub-models employed for analysis of irrigation and electric power. The water system of the interconnected basins is operated to minimize water stress. Results suggest that, with or without climate change, U.S. average annual water stress is expected to increase over the period 2041 to 2050, primarily because of an increase in water requirements, with the largest water stresses projected in the South West. Policy to lower atmospheric greenhouse gas concentrations has a beneficial effect, reducing water stress intensity and variability in the concerned basins.

Contents

1. INTRODUCTION

Water availability is a growing global concern (UN, 2012), and many rivers are affected by water scarcity and quality issues. Troubling examples include the Ganges and Indus in India; the

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Amu Dar'ya and Syr Dar'ya in Central Asia; the Murray and Darling in Australia; and the Yellow and Yangtze in China (Postel, 2000). The U.S. is no exception, with the Colorado and the Rio Grande rivers so severely exploited that they often do not reach the oceans. Heavy exploitation of many U.S. water resources is the consequence of growing population and economic activity, and lack of conservation measures. Under the threat of climate change, and consequently a change in surface hydrology, the water issue is even more pressing.

To investigate the issue of water allocation and scarcity for the U.S., we develop a specially tailored version of the Integrated Global System Model–Water Resource System (IGSM-WRS) model (Strzepek *et al.*, 2012b), which draws on the water system module (WSM) developed by the International Food Policy Research Institute (Rosegrant *et al.*, 2008). WRS allows the linkage of WSM with the IGSM (Sokolov *et al.*, 2005). **Figure 1** shows the linkages between the IGSM and WRS components developed for water system studies. Taking advantage of data available for the U.S., we incorporate a number of changes in the model documented in Strzepek *et al.* (2012b) and applied at the global level by Schlosser *et al.* (2013). These modifications include:

- U.S. waters are modeled at a 99-basin level, instead of the 14-basin U.S. aggregation when the model is applied at global scale.
- Economic inputs to the analysis are supplied by an 11-region model of the U.S., replacing the single-nation representation in the global application.
- Inter-basin transfers, which are not handled in the global application, are included.
- More complete representations of the systems supplying irrigation water and of management practices at the crop level are included.
- A better estimation of energy demand (denoted by the 'energy' linkage between the U.S. Regional Economic Policy (USREP) model (Rausch *et al.*, 2010) and WRS in Figure 1) is incorporated, allowing a better estimation of water requirements for mining and thermoelectric power generation.
- Detailed estimations of water requirements for public supply and self-supply sectors are added.

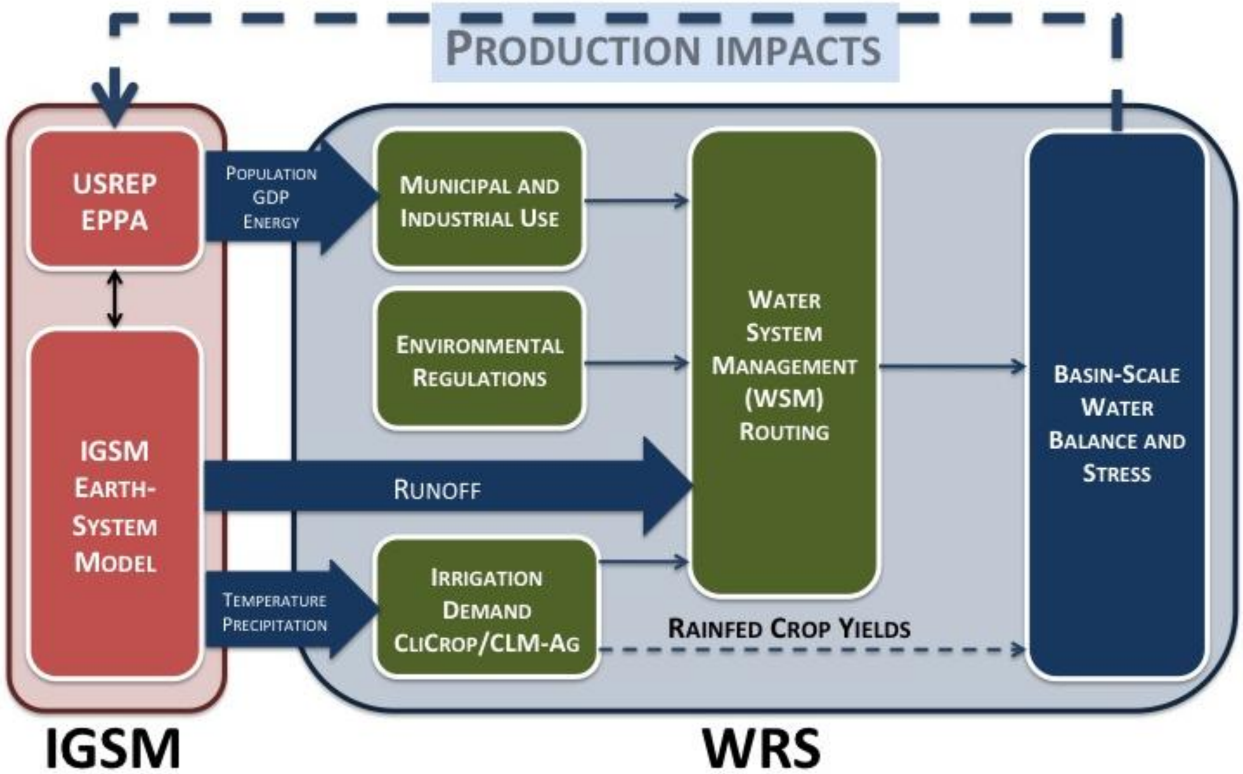

Figure 1. Schematic of the IGSM-WRS model illustrating the connections between the economic and climate components of the IGSM framework and the Water Resource System (WRS) component.

Notes: The solid arrows represent linkages between modules developed in this study. The dashed arrows represent future developments. The economic component of the IGSM—applying the Emissions Prediction and Policy Analysis (EPPA) model in a global setting, or USREP in a U.S. setting—drives municipal and industrial water requirements. The geophysical component of the IGSM (the Earth System Model) simulates hydro-climatic conditions determining water resources and irrigation requirements. Water requirements, water resources and environmental regulations are the main components of the Water System Management routing which computes water balance and water stress at the basin scale.

To simplify the notation, we refer to this version of the IGSM-WRS framework as the WRS-US model. Description of this application of the model is organized as follows. First, in Section 2, we provide a brief summary of the structure of the model. Section 3 describes the estimation of water resources, and Section 4 presents the estimation of the various water uses. Section 5 explains the handling of environmental requirements. Then, in Section 6, we show the results of the U.S. application. In these simulations, water requirements and availability are explored along with estimation of water deficits, taking account of six sets of modeled climate conditions by 2050: two scenarios of greenhouse gas (GHG) policy, and three patterns of distribution of climate over latitude bands. Section 7 concludes.

2. MODEL STRUCTURE

The 99 WRS-US river basins follow the Assessment Sub-Region (ASR) delineation set out by the U.S. Water Resources Council (1978). These ASRs are presented in **Figure 2** along with the ASR identifying numbers. The color scheme from dark green to red represents distance of the ASR from its outlet to the ocean, Great Lakes, Canada or Mexico. Dark green basins are most distant from their outlet and red are those basins that include the basin outlet. The purple ASRs are closed and do not flow outside the basin. A list of ASR names is provided in Appendix A.

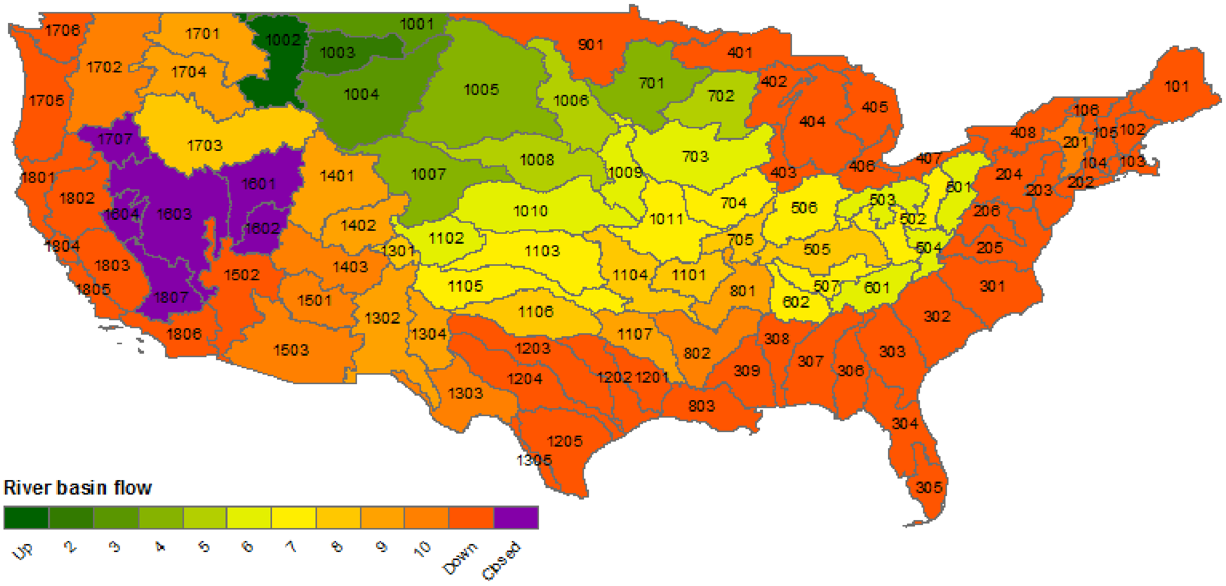

Figure 2. River basins in the continental U.S. and river flow structure.

Note: A listing of ASR names is provided in Appendix A.

The WRS-US models water resources and requirements[1] and allocates the available water to different users each month while minimizing annual water deficits (i.e. water requirements that are not met). To do so, the model solves the allocation of water for each ASR simultaneously for the months of each year. Upstream basins are solved first, and the calculation proceeds downstream following the structure of river flows. Water spilled from upstream basins becomes the inflow for downstream basins. Closed basins are solved last.

Reservoir operation is essentially the same as in the global version and details can be found in Strzepek *et al.* (2012b). A schematic of the model at the ASR level adapted for the U.S. is presented in **Figure 3**. All water storage in the ASR is aggregated into a single virtual reservoir (STO). Total water supply (TWS) is comprised of this surface water storage plus groundwater supply (GWS). In this application we do not consider water from desalination (DSL) or groundwater recharge (two model modifications represented by the red arrows). STO receives

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[1] The term 'requirements' refers to the water uses for each sector, which in this study are estimated based on recent experience and therefore implicitly assume current or recent prices.

the river basin runoff (RUN) and inflows from upstream basins (INF). This version of WRS also accounts for inter-basin transfers (IBT). Part of the STO is lost through evaporation (EVP).

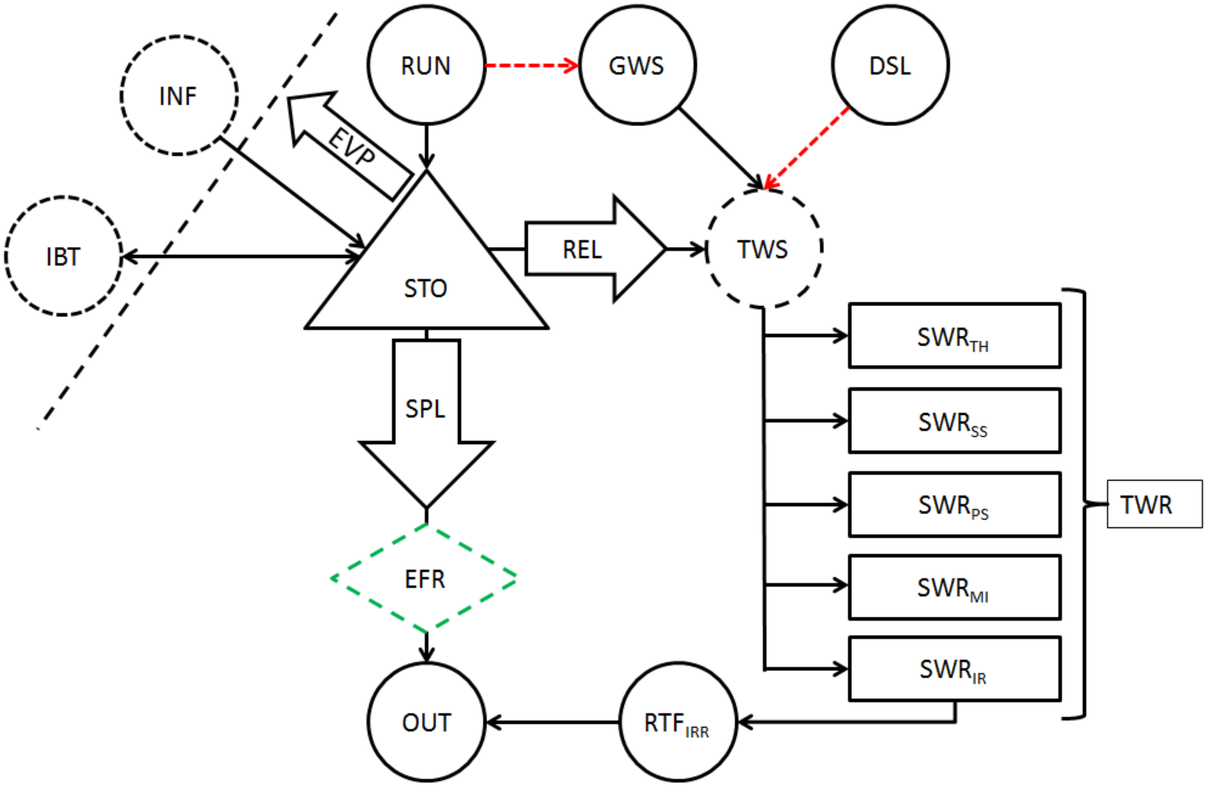

Figure 3. Schematic of the Water System Management (WSM) module at ASR scale in the WRS-US.

Notes: The total water requirement (TWR) is calculated by summing municipal (SWR_{MUN}), industrial (SWR_{IND}), livestock (SWR_{LVS}), and irrigation (SWR_{IRR}) requirements. Surface water supply comes from inflow from upstream basins (INF), and local basin natural runoff (RUN) and it goes into the virtual reservoir storage (STO) where evaporation loss (EVP) is deducted. The reservoir operating rules attempt to balance the water requirements (TWR), with the total available water (TAW). Non-surface supplies: groundwater supply (GRW) and desalination supply (DSL), are used first and any remaining requirements are met by a release from the virtual reservoir (REL). Additional releases (SPL) are made to meet environmental flow requirements (EFR).

Releases from surface storage (REL) and GWS constitute the total water supply (TWS), which is used to fulfill the water requirements of the different sectors (SWR). In the

WRS-US, we identify five sectors (compared to four in the global application): thermoelectric plant cooling (TH), irrigation (IR), public supply (PS), self-supply (SS) and mining (MI). For all sectors, except irrigation, those water requirements are represented by consumptive use on the assumption that any return flow (withdrawal in excess of consumption) is small and likely returned to the ASR storage within the month. This assumption is not appropriate for irrigation, because return flow may be substantial and may not be returned to the ASR storage immediately.

Instead, the water lost in conveyance and field inefficiency is accounted as a return flow (RTF_{IR}) which will contribute to the outflow of the basin (OUT) in the next month.

The degree to which total water requirements (TWR) are met is determined by the total water supplied (TWS). This water is allocated proportionally among all sectors, except irrigation. Water is only available for irrigation if there is sufficient water to meet the requirements of all other sectors.[2] If total water supplied is insufficient to meet the non-irrigation requirements, those sectors take an equal proportional cut.

After accounting for water supply to the different sectors and evaporation from surface storage, excess water in each ASR is spilled onto its downstream basin (SPL) while respecting a minimum environmental flow (EFR) to constitute the outflow, which is the inflow of the downstream ASR.

3. WATER RESOURCES

Surface water resources are influenced by local climate, which in turn is influenced by GHG concentrations in the atmosphere. We project future climatic conditions using global emissions scenarios analyzed by the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005). These GHG emissions serve as inputs into the Earth System component of the Integrated Global System Model (IGSM), as illustrated in Figure 1 (Sokolov *et al.*, 2005). To provide meteorological variables at the relevant scales of the WRS, we then downscale the two-dimensional (altitude, latitude) climate results from the IGSM using the Hybridized Frequency Distribution (HFD) approach (Schlosser *et al.*, 2012). Within the HFD procedure, we chose representative shifts in the regional climate patterns or 'climate-change kernels' as discussed in Section 6. The projected regional variables are used to determine runoff. The estimated total basin runoff, accounting for upstream basin inflows and inter-basin transfers, comprise the surface water resources, which are then combined with supply from groundwater. Each of these components is estimated at the ASR level following the methodology outlined below.

3.1 Runoff

Runoff represents the water flowing over the surface and immediately below the surface of the ground and is caused by rainfall or snow melt. In this study, runoff is estimated using the biogeophysical portion of the Community Land Model (CLM, version 3.5) developed at the National Center for Atmospheric Research (NCAR, 2012) through a collaborative effort by the scientific community-at-large. CLM models soil-plant-canopy processes of the surface and subsurface that include key fluxes to the hydro-climate system. The hydrologic component of CLM estimates runoff taking explicit account of infiltration controls, canopy interception, root-active and deep-layer soil hydro-thermal processes, soil evaporation, evapotranspiration, snowpack, and melt. As described in Strzepek *et al.* (2012b), CLM provides gridded runoff data

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[2] This assumption is based on the relative economic value of water in these different uses. Where institutional arrangements (contracts, treaties, water laws) intervene, these factors can be added to the algorithm for affected ASRs.

to the ASRs and the management of the runoff routing is endogenously determined by WRS-US. Inflows from upstream basins are sequentially estimated starting by the further upstream basins, which have no inflow. For the neighboring downstream basins, inflows are the sum of water spilling from each upstream basin. No water flows into, or spills from, closed basins. These basins are situated in desert regions such as the Sierra Nevada, where the limited precipitation is depleted through evaporation.

Recent studies show that CLM simulates mean annual cycles of runoff over continental-scale basins rather well (e.g., Lawrence *et al.*, 2011). Yet at the scale of the 99 U.S. ASRs employed herein, both the mean and variability of CLM's runoff estimates require further refinement. As described in Strzepek *et al.* (2012b), CLM's monthly runoff at each basin is adjusted using the MOVE12 technique. MOVE12 requires estimates of the first two moments (mean and standard deviation) of runoff at every ASR. However, observed data on natural flow at the ASR basins (which most closely represents total runoff generated by CLM) are not available due the human interference via river management (e.g., dams, consumption). We therefore use runoff estimates provided by the U.S. Water Resources Council's (USWRC) 1978 national water assessment (U.S. Water Resources Council, 1978). This dataset produces statistical estimates of monthly natural flow for the 99 ASRs using observed gauged flow data, data on water withdrawal, storage and consumption from 1954 to 1977. Similar to the results obtained with the global MOVE12 procedure with CLM (Strzepek *et al.*, 2012b), the procedure successfully adjusts CLM runoff to match that of the USWRC estimates (see Figure 4). Accordingly, these adjusted runoff values (at a monthly timescale) are then provided as runoff (RUN) within the WSM module presented in Figure 3.

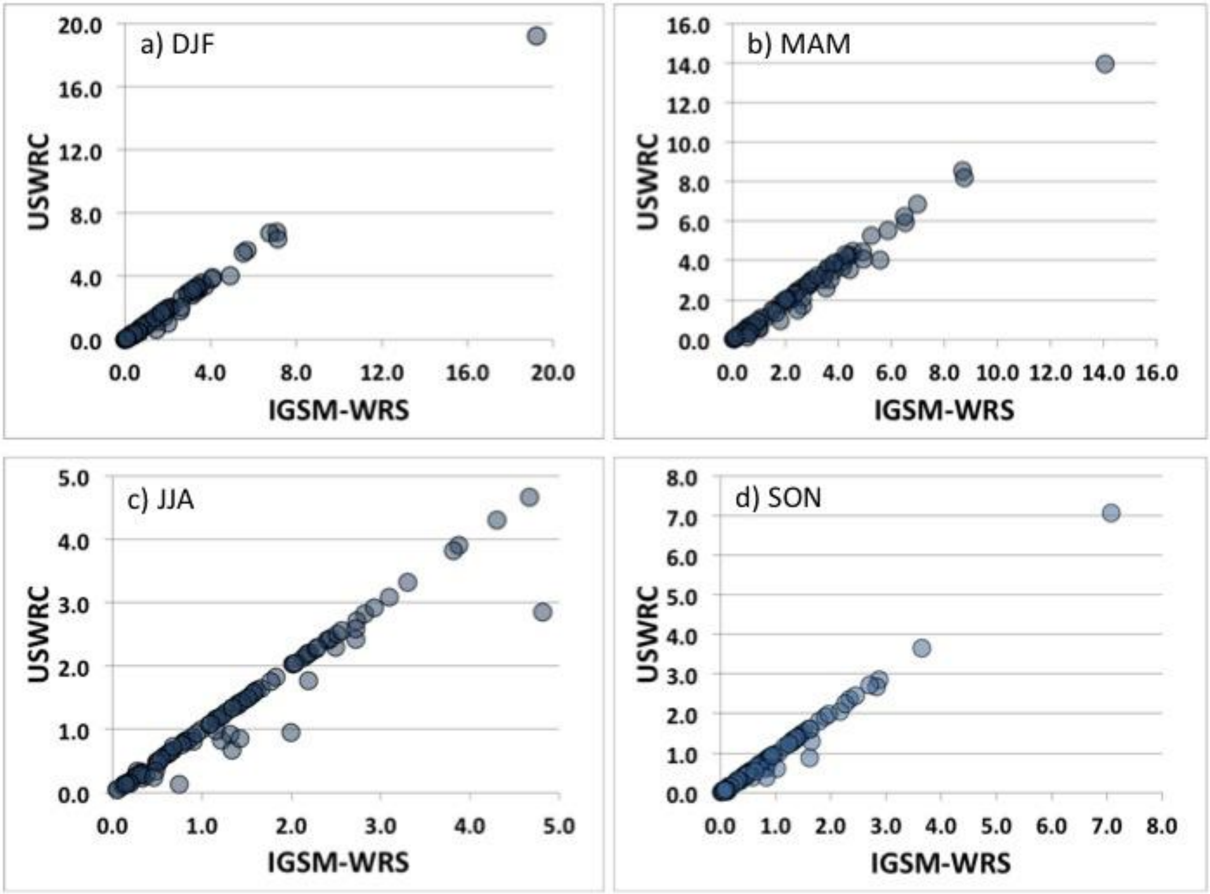

Figure 4. Seasonal-mean natural flow of the CLM values adjusted via the MOVE12 procedure (abscissa values) compared against the empirical estimate of the USWRC (1978) study (ordinate values) for the period 1954 to 1977. Scatterplots present the comparisons of the 99 ASRs seasonal mean for a) December-February (DJF), b) March-May (MAM), c) June-August (JJA), and d) September-November (SON). All flow values are given in units of billion cubic meters (BCMs) per month.

3.2 Inter-Basin Water Transfers

Water is transferred from water-abundant basins to water-limited ones via conveyance systems such as canals and aqueducts. In the U.S., these transfers are most common in the West. We model them by assuming that a fixed amount of water is transferred annually based on past observations. In this application, we account for several of these transfers, including:

- From the Colorado River to the Metropolitan Water District, the Imperial Irrigation District and the Coachella valley in California through the All American Canal–Lower Colorado basin (ASR 1502) to Southern California basin (ASR 1806) (U.S. Bureau of Reclamation, 2009).
- A further transfer from the Colorado River to Southern California via the Colorado River aqueduct–Lower Colorado basin (ASR 1502) to Southern California basin (ASR 1806) (Zetland, 2011).

- California State Water Project transfers from the Sacramento Valley to the San Joaquin valley–Sacramento-Lahontan basin (ASR 1802) to the San Joaquin-Tulare basin (ASR 1803)—and from the Tulare region to Southern California–San Joaquin-Tulare basin (ASR 1803) to the Lahontan-South basin (ASR 1807) (Connell-Buck *et al.*, 2011).

3.3 Groundwater

Groundwater reservoirs (aquifers) represent an important source of fresh water as they store 25% of global freshwater (USGS, 2012). The depletion and recharge of these reserves is a controversial issue globally (van der Gun, 2012). Numerous methods have been devised to estimate groundwater recharge, but these methods are prone to many uncertainties and errors (Scanlon *et al.*, 2002). In this study, groundwater supply (GWS) is assumed to be limited to the 2005 groundwater uses estimated by U.S. Geological Survey (USGS) (2011). We do not model groundwater recharge. Improvements to the groundwater component of the WRS-US are a topic of future research. However, even without explicitly representing groundwater recharge, the model allows the development of different scenarios of groundwater withdrawal based on different estimates or assumptions of sustainable withdrawals, or reductions in withdrawal due to depletion.

4. SECTORAL WATER REQUIREMENTS

As presented in the **Figure 5a**, fresh water in the U.S. is mainly withdrawn for thermoelectric cooling and irrigation, which represented 42% and 36% of total fresh water respectively in 2005 (USGS, 2011). In terms of consumption (**Figure 5b**), however, thermoelectric cooling is a small sector, consuming only 4% of the water withdrawn for that purpose. Irrigation, on the other hand, consumes 60% of the water withdrawn and is the largest consuming sector. As explained in Section 2, in estimating water requirements we take account of reuse. To estimate requirements for thermoelectric cooling, public supply, self-supply, and mining, therefore, we consider their water consumption since the non-consumed water is assumed to be returned immediately to the ASR and available for other purposes. For irrigation, however, we take withdrawal as the measure of its water requirement because the return flow is accounted in the outflow of the basin for use in downstream basins (RTF_{IRR} in Figure 3). This combination of estimates leads to **Figure 5c**. It reflects the relative scale of these uses as imposed in the model and shows that the largest user in the U.S. is irrigation, with 87% of total water requirements measured at the ASR level.

The remainder of this section presents the methods used to estimate water requirements at the ASR level for each sector. These requirements are projected based on population and GDP growth estimated by the U.S. Regional Economic and Environmental Policy (USREP) model (Rausch *et al.*, 2010). USREP is a recursive–dynamic multiregion, multicommodity general equilibrium model of the U.S. economy. USREP is based on a comprehensive energy–economic data set that features a consistent representation of energy markets in physical units as well as detailed accounts of regional production, bilateral trade, and energy resources. The data set merges detailed state-level data for the U.S. with national economic and energy data. Social accounting matrices (SAM) in our hybrid dataset are based on data from the IMPLAN (IMpact analysis for PLANning) data (Minnesota IMPLAN Group, 2008) and U.S. state-level accounts on energy balances and prices from the Energy Information Administration (2009). Population growth is exogenous in USREP, and projections by U.S. state are taken from the U.S. Census Bureau (2000). USREP has a time step of two years and divides the continental U.S. into 11 regions. The regional population and GDP growth rates estimated by USREP are extended to annual figures for the corresponding ASRs. Future water requirements for irrigation are projected indirectly from USREP projections via the effect of projected emissions on climate.[3]

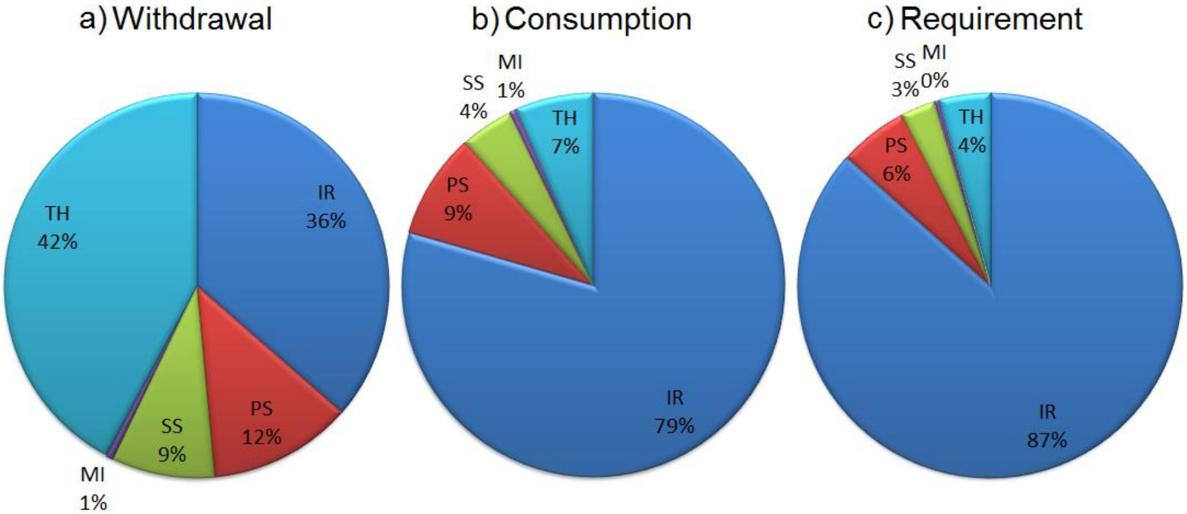

Figure 5. U.S. water withdrawal, consumption and requirement by sector in 2005.

Notes: Pie charts constructed using withdrawal and consumption data estimated by USGS (2011). Water requirements for irrigation correspond to irrigation withdrawal. Requirement for the other sectors correspond to consumption.

4.1 Thermoelectric Cooling

Water withdrawn for power plant cooling either goes through cooling towers or ponds before being reused (recirculating or recycle systems) or is returned to the stream (once-through systems). The share of withdrawn water that is consumed depends on the cooling system employed (Templin *et al.*, 1997). In recirculating/recycling systems, water goes through cooling towers or ponds and is then reused so that a large share of the water withdrawn from the stream is consumed. In once-through systems, the water is used once and returned to the stream so that a relatively small share of the withdrawn water is consumed. U.S. power systems requiring thermoelectric cooling are represented using the Regional Energy Deployment System (ReEDS) model (Short *et al.*, 2009), a recursive-dynamic linear programming model that simulates the least-cost expansion of electricity generation capacity and transmission, with detailed treatment of renewable electric options. ReEDS is composed of 134 power control areas (PCAs) and

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[3] USREP is run with external conditions (prices, trade) set to be consistent with the global simulations of the EPPA model (Paltsev *et al.*, 2005) that are input to the climate simulations.

models electricity generation by fuel type (fossil fuel, nuclear) and cooling system (once-through, recycle). The ReEDS model is fully integrated in USREP, i.e. electricty-sector optimization is fully consistent with the equilibrium response of the economy including endogenously determined electricity demand, fuel prices, and goods and factor prices. This allows us to include general equilibrium economy-wide effects while capturing important electricity-sector detail with respect to technology innovation and investments in transmission capacity. In particular, ReEDS allows us to provide electricity-sector output that is sufficiently resolved in terms of space and technology to parameterize the WRS model component.

The integrated USREP–ReEDS model and the methodology used to linked the two models is presented in Rausch and Mowers (2012). Based on the electricity system demand provided by the ReEDS model, monthly withdrawal and consumption in thermoelectric cooling is estimated using the Withdrawal and Consumption for Thermo-electric Systems (WiCTS) model (Strzepek *et al.*, 2012a). In this version of the model, we estimate water requirements for thermoelectric cooling (SWR_{TH}) considering consumption only, assuming as noted above that non-consumed withdrawals are returned to the ASR within the same period. Estimates of withdrawal for this sector will be useful in future analyses of the effect of thermoelectric power plants on water temperature, or of stream flow and temperature on powerplant operations.

4.2 Irrigation

To estimate water use for irrigation, we need to consider various aspects of the irrigation system. As represented in **Figure 6**, water withdrawn from the stream or reservoir is delivered to the cropping field via a conveyance system (e.g., canal, pipes). Depending on the type of conveyance system, part of the water withdrawn is lost through seepage and/or evaporation. This fraction of water reaching the field (i.e. delivery at the field) is represented by conveyance efficiency. The water delivered at the field is either applied to crops directly or used for irrigation-related activities (e.g., frost prevention, leaching) or lost in the field distribution system. The fraction of water reaching the plant is called field efficiency and depends on the irrigation system used (e.g., sprinkler, drip).

To estimate the water requirement at the crop level, we use the CliCrop model (Fant *et al.*, 2011), which estimates crop water required at the root to eliminate all water stress. Actual irrigation practices may not apply optimal amounts of water and CliCrop estimates may imperfectly represent water requirements for some crops. For these reasons we develop a crop-specific management factor and a region-specific calibration that allows us to adjust modeled irrigation water use to observed use. As a benchmark for estimating this factor, we use water consumption data extracted from the Farm and Ranch Irrigation Survey (FRIS), which provides detailed information on farm irrigation practices in 2003 (USDA, 2003). FRIS reports, for each crop and each state, the amount of irrigation water consumption at the field and the irrigated area. We explain each of these steps, working right to left in Figure 6.

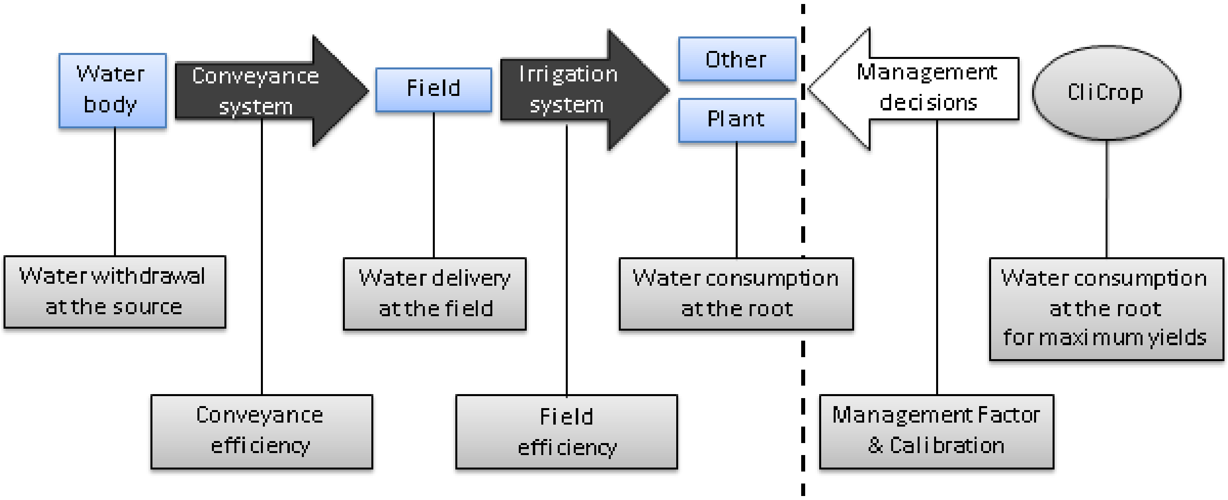

Figure 6. Schematic of Irrigation System Model in WRS-US.

Notes: Irrigation requirements at the root are estimated by the biophysical model CliCrop and adjusted by management practices. Ultimate withdrawals to meet the requirements take account of losses in the field and in conveyance from the source to the field.

Water consumption at the root level

CliCrop is a biophysical model developed for use in integrated assessment frameworks (Fant *et al.*, 2011). It is global, fast, and requires a minimal set of inputs. It is based on the Food and Agriculture Organization (FAO)'s CropWat model (Allen *et al.*, 1998) for crop phenology and irrigation requirements, and on the Soil and Water Assessment Tool (SWAT, Neitsch *et al.*, 2005) for soil hydrology. CliCrop runs on a daily timescale, has a 2°×2.5° grid resolution for the globe, and estimates crop water requirements (in mm/crop/month) to obtain maximum yields under given weather conditions for 13 of the most commonly grown crops. The irrigation requirement at the roots of the plant is defined as the difference between the evapotranspiration requirement (as defined by Allen *et al.*, 1998) and the actual evapotranspiration as computed by CliCrop. For water requirements of crops not modeled by CliCrop, we use crops with similar irrigation needs as proxies. **Table 1** presents the generic crops used in CliCrop as proxies for crop water requirements in the U.S. For each crop, the planting date has been specified according to data from the Centre for Sustainability and the Global Environment (SAGE)—University of Wisconsin (Sacks *et al.*, 2010).

Annual water consumption CON_{IR} is estimated at the county level for each crop using monthly crop water consumption estimated by CliCrop and irrigated area, ARE_{IR}, sourced from FRIS: [4]

$$CON_{IR} = \sum_{month}\sum_{crops} CON_{IR}(crop, month) \times ARE_{IR}(crop) \tag{1}$$

To obtain water consumption at the ASR level, we aggregate county level consumptions for all counties lying within the ASR.[5]

Table 1. Correspondence between crops modeled by CliCrop and actual crops.

CliCrop crop type	Actual crop type
Forage/Alfalfa	Forage/alfalfa Pastureland Orchards
Cotton	Cotton
Grains or barley	Grains or barley
Groundnuts	Groundnuts
Maize	Maize (grain and silage) Berries
Potatoes	Vegetables Other
Pulses	Pulses
Rice	Rice
Sorghum	Sorghum
Soybeans	Soybeans
Sugar beets	Sugar beets
Sugar cane	Sugar cane
Wheat (average spring/winter wheat)	Wheat, spring and winter

Crop specific management factor

The Clicrop estimate of water requirements corresponds to the level of water necessary to eliminate water stress in the crop and, assuming that other factors are not limiting, achieve maximum yield. In practice, however, farmers may not aim to maximize yields. For instance, lower valued crops such as forage may not justify irrigation expenses associated with maximum yields. For other crops, water is used for irrigation related activities (e.g., field flooding to harvest cranberries). Alternatively, the CliCrop representation may be imperfect as it uses a

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[4] As the delineations of states and ASRs do not match perfectly, we estimate water consumption data at the county level. FRIS provides irrigated area by crop. However, these data are provided at the state level only. To obtain irrigated area for each crop at the county level, we use total irrigated area estimated by USGS (2011) for 2005 at the county level (USGS provides irrigated area at the county level but does not detail irrigated area by crop). We allocate state level irrigated areas from FRIS using the ratio of total irrigated area at the county level within each state from USGS following the formula:

$$ARE_{IR}(crop, county) = ARE\_FRIS_{IR}(crop, state) \cdot \frac{ARE\_USGS_{IR}(county)}{\sum_{state} ARE\_USGS_{IR}(county)}$$

[5] For counties overlapping several ASRs, the matching is based on the share of the county area lying within the ASR.

proxy for some crops. To account for varying irrigation practices and modeling errors, we estimate for each crop the fraction of water actually consumed compared to the consumption amount estimated by CliCrop. Actual water consumption data (i.e. water used to obtain actual yields) are obtained using FRIS survey data on water delivery at the field, to which we apply a field efficiency (shown in Figure 6 and presented in the next sub-section).

To estimate the U.S.-wide crop specific management factors, *M*, we employ a univariate regression for each crop at the county, level:

$$CON_{IR,FRIS}(crop, county) = M(crop) \times CON_{IR,CLICROP}(crop, county) + \varepsilon \tag{2}$$

where $CON_{IR,FRIS}$ is the irrigation water consumption at the root calculated from FRIS data for 2003.[6] We consider $CON_{IR,CLICROP}$ as an annual average of CliCrop water consumption over the period 1998 to 2003, as survey responses from farmers might not be strictly representative of 2003 (most water withdrawals are not metered) but rather a short-term average of water uses. The results of these regressions are reported in **Table 2**. Management factors lower than 1.0 indicate that farmers irrigate less than is necessary to obtain maximal yields. As expected, small M factors are obtained for low value crops such as pasture. For other crops, management factors higher than 1.0 capture irrigation related uses (e.g., berries) or imperfect crop representation by CliCrop.[7] We estimate future water consumption for each crop by multiplying CliCrop crop water consumption by the corresponding management factor.

Table 2. Univariate regression results for the estimation of the management factors.

Crops	M	Standard errors	Observations	R-squared
Forage	0.695***	(0.00704)	1,570	0.861
Pasture	0.579***	(0.00692)	2,564	0.732
Cotton	0.695***	(0.0237)	284	0.753
Grains	0.902***	(0.0369)	154	0.796
Groundnuts	0.466***	(0.00818)	134	0.961
Maize	1.304***	(0.0152)	1,036	0.876
Pulses	1.390***	(0.0492)	151	0.842
Rice	0.664***	(0.0209)	108	0.904
Sorghum	0.570***	(0.0114)	200	0.926
Soybeans	1.311***	(0.0216)	569	0.866
Sugarbeets	1.335***	(0.0724)	60	0.852
Wheat	0.562***	(0.0125)	458	0.815
Vegetables	1.669***	(0.0249)	1,210	0.788
Potatoes	1.837***	(0.0333)	3,082	0.497
Berries	1.334***	(0.0425)	239	0.805
Orchard	1.837***	(0.0657)	668	0.540
Other	0.824***	(0.00644)	925	0.947

Notes: *** p<0.01, ** p<0.05, * p<0.1

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[6] See paragraph on water consumption at the field for details regarding the calculation of water consumption at the root using the system efficiency.

[7] For wheat, the low coefficient can be explained by the fact that this crop is irrigated differently in winter and summer. The allocation of irrigation across the year is not known, so we assume that CliCrop takes an average of irrigation need between the two seasons. For vegetables, the high management factor is due to the fact that vegetables are proxied by potatoes in CliCrop.

Region specific irrigation-related uses

A portion of irrigation water is also used for pre-irrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching of salts from the root zone (Kenny, 2004). Most of these irrigation-related uses are region specific (e.g., soil leaching in dry regions, frost protection in cool regions). However, CliCrop is not designed to capture these uses. FRIS data, on the other hand, include all irrigation-related water uses but do not distinguish the amount of water used specifically for irrigation from the water used for other purposes. To estimate these other irrigation uses, we calculate irrigation consumption for other purposes at the ASR level, CON_{IRO}, as the difference between FRIS and CliCrop water consumption at the county level:

$$CON_{IRO} = \sum_{cnt} CON_{IR,FRIS}(crop, county) - \sum_{cnt} M(crop) \times CON_{IR,CLICROP}(crop, county) \qquad (3)$$

CON_{IRO} is assumed to remain constant at the 2005 level (this assumption merits further study as water resource changes might influence irrigation related water consumption). To obtain monthly calibration, we spread the calibration constant across the year proportionally to irrigation water consumption estimated by CliCrop.

Field efficiency

As explained above, some water losses occur at the irrigation apparatus level: furrows are, for example, less efficient than sprinklers or drip irrigation. These losses are represented by irrigation field efficiencies *FEF*, also called application efficiencies. To account for these water losses, we calculate the average efficiency for each technique (Kenny, 2004) weighted by the area over which such system is in use in each state. We assume that the field efficiency is the same for each county within a state. Field efficiencies at the ASR level are represented in **Figure 7**.

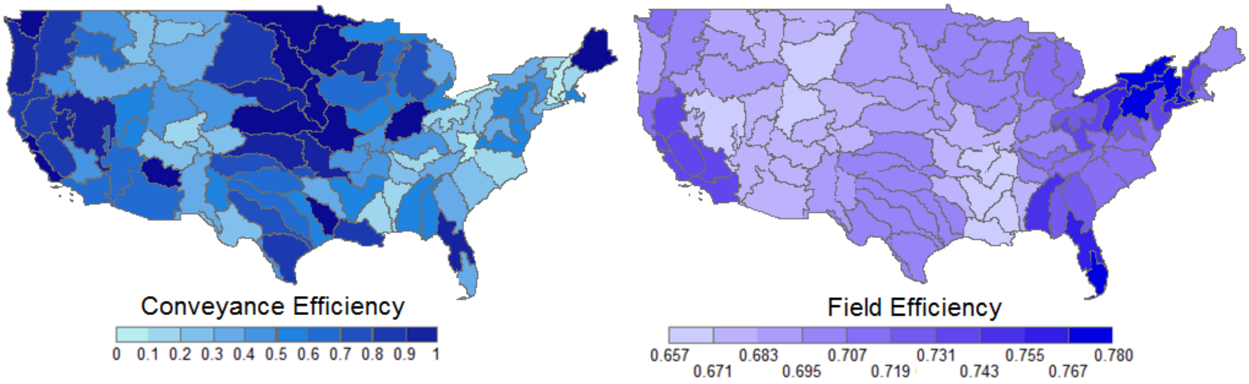

Figure 7. Conveyance and field efficiencies.

Water delivery at the field

Water delivery at the field represents the amount of water delivered to the farm for irrigation purposes. It is estimated by applying the field efficiencies, *FEF*, discussed above, to water consumption at the root for crop and other irrigation related purposes:

$$DEL_{IR} = \frac{\sum_{cnt,crop} CON_{IRO}(crop, county) + M(crop) \times CON_{IR,CLICROP}(crop, county)}{FEF} \tag{4}$$

We then aggregate all the county level water consumption at the ASR level.

Conveyance efficiency

A major portion of agricultural water loss occurs in transport between the source and the field. This loss is usually represented by a conveyance efficiency (*CEF*), which is calculated as the ratio of water reaching the field over the water withdrawn at the source (Howell, 2003). We determine conveyance efficiency for each ASR using county irrigation data of withdrawal sourced from USGS (2011) for 2005 and delivery at the field data from FRIS for 2003.[8] Conveyance efficiencies calculated for each ASR are shown in Figure 7.

Water withdrawal at the stream

Irrigation water withdrawal at the stream is the total amount of water diverted from the natural hydrologic system for irrigation purposes. To calculate water withdrawal, *WTH*, we apply the conveyance efficiency, *CEF*, to the field delivery, *DEL*:

$$WTH_{IR} = DEL_{IR} / CEF \tag{5}$$

4.3 Other Sectors

Other than irrigation and thermoelectric cooling purposes, water is used for residential (domestic), industrial, commercial, mining, and livestock and fisheries. These requirements are classified into three groups: public supply, self-supply, and mining. Public supply withdrawal refers to “water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections” (USGS, 2011). Public supply water withdrawals include water use for residential purposes, commercial activities, industrial activities, public uses and losses. Self-supply water withdrawal represents “water withdrawn from a groundwater or surface-water source by a user rather than being obtained from a public supply” (USGS, 2011). Self-supplies include water use for residential purposes, commercial, industrial, livestock and aquaculture activities. Mining water withdrawal is defined as “water use during quarrying rocks

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[8] Water delivery data and water withdrawal data are not available for the same year.

and extracting minerals from the land" (USGS, 2011). Water use for shale gas fracking is included in the Mining category.[9]

Water withdrawal for each of these sectors is estimated econometrically using water data collected at the county level by USGS (2011). Public supply withdrawals are estimated as a function of population and GDP per capita. Self-supply and mining withdrawals are determined by sectoral GDP drawn from USREP model results.[10] Details of the econometric analysis are provided in Appendix B.

Due to data limitations, we make several assumptions in order to comply with the model definition (see Section 2), which treats the water requirements for these sectors (SWR) not as withdrawal but as consumption. First, consumptive use data, which represents the amount of water not returned to the source for immediate reuse, are only available until 1995. To calculate water consumption for other years, we assume that the proportion of water consumption in water withdrawal remains the same as in 1995. Second, water withdrawals for the public supply, self-service, and mining sectors are only estimated annually. To obtain monthly water values, we assume that withdrawals are spread evenly across the year (this assumption can be modified in future development of the model). Third, the data set does not provide details regarding water demanded that was not met. This might be the case for some sectors, such as public supply for example, when a city applies water restrictions during dry periods. We assume that estimated water requirements were always met by water supplied.

Future water requirements for these sectors are projected by estimating future consumption. Sectoral consumption is assumed to be a constant share of sectoral withdrawals, which is obtained by applying the population and GDP growth estimates from the USREP model to the corresponding variables in the regression for each sector (see Appendix B).

5. ENVIRONMENTAL WATER REQUIREMENTS

The protection of the fauna and flora of aquatic systems is an important concern for the U.S. Environmental Protection Agency (EPA, 2012). In the U.S., water is regulated by national legislations such as the 1969 National Environmental Policy Act and the 1972 Clean Water Act. In addition, water resource management is decentralized by state and region, which has led to a variety of additional regional water policies (Hirji and Davis, 2009). These policies usually protect water ecosystems through the regulation of water levels and flows.

To model these environmental requirements, we apply two constraints on surface water in the model. First, releases from surface storage are limited to a proportion of the storage capacity in order to respect an environmental minimum storage threshold. Minimum lake levels are usually determined as an elevation below which the water body should not fall, and they vary by district.

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[9] Water use for shale gas is not detailed in the data for the base period. However, O'Sullivan (2012) estimates water requirements for this activity at less than 15 MCM in 2005, which represents around 0.016% of total water withdrawals. This activity, although predicted to increase in the future, does not warrant separate representation in this study.

[10] The valued-added for the mining sector is based on coal, gas, and oil production but also accounts for other mining activities (i.e. iron ore mining and other metals).

We assume a minimum surface water storage of 10% of the surface water storage capacity. Second, the spill from each basin must meet a minimum river flow or environmental flow requirement (EFR). The determination of the volume and timing of these flows should also be determined locally. According to Smakhtin *et al.* (2004), flows that are exceeded 90% of the time (Q90 flows) are sufficient to maintain riparian zones in ‘fair’ condition, and provide a reasonable measure of EFRs. In this application, we set an EFR equivalent to 10% of mean monthly flow for each ASR.

6. PROJECTIONS THROUGH 2050

Water uses and resources are modeled to 2050, considering both alternative emission scenarios and potential regional shifts in climate patterns. Starting at 2010, two emission scenarios are considered: (i) an unconstrained emissions scenario (UCE) assumes that no specific effort is made to abate GHG emissions; and (ii) a ‘Level 1 stabilization’ (L1S) scenario assumes that GHG emissions are restricted to limit the atmospheric concentration of CO_2 equivalent GHGs to 450 ppm (Clarke *et al.*, 2007). These scenarios serve as inputs into the IGSM 2-D model using median parameter values of climate sensitivity, rate of ocean heat uptake, and aerosol forcing (e.g., Forest *et al.*, 2008). To provide meteorological variables at the relevant scale for WRS, we then downscale the results using the HFD approach. Within the HFD procedure, we chose two representative shifts in the regional climate patterns, or ‘climate-change kernels’—as determined from climate model projections from the Coupled Model Intercomparison Project Phase 3 (CMIP3)(Meehl *et al.*, 2007)—to explore a plausible range of relatively dry and wet trending conditions over the majority of U.S. ASRs. Results from the WRS scheme forced by these dry and wet climate-change kernels, then provide insight into the impact of uncertain regional climate change on water-management risks. Given these considerations, we find that the Geophysical Fluid Dynamics Laboratory (GFDL) Version 2.1 (Delworth and Coauthors, 2006) and the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) version 3 (Collins *et al.*, 2006) provide representative ‘dry’ and ‘wet’ projections, respectively (see **Figure 8**). Hereafter, we refer to these climate model outcomes as U.S.-DRY and U.S.-WET. Generally speaking, the U.S.-DRY pattern is characterized by substantially drier conditions (particularly in the summer) throughout most of the U.S. The widespread relative decreases in precipitation will coincide with strong relative warming – as global temperature increases. The U.S.-WET case replaces the drying conditions in many regions with relatively wetter and cooler trends as precipitation increases and the warming over the continent is substantially reduced (relatively to their U.S.-DRY conditions).

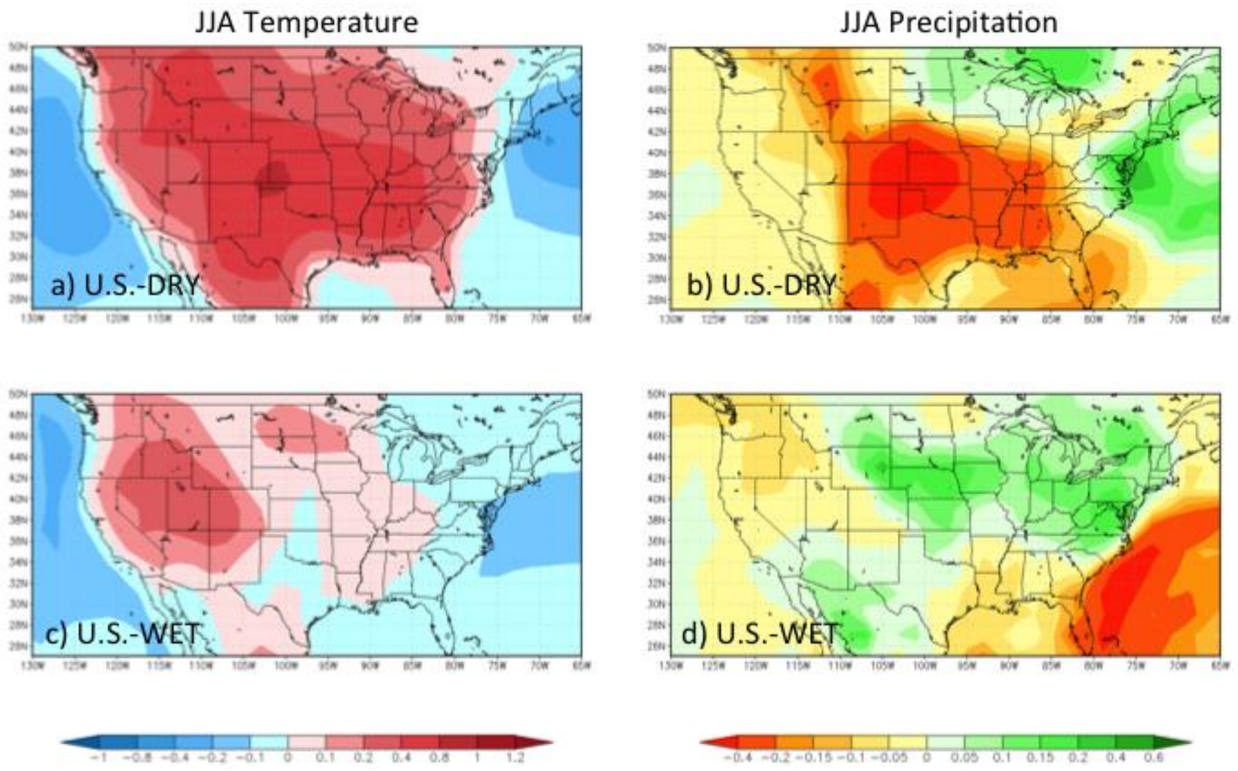

Figure 8. Samples of the climate-change kernels of Schlosser *et al.* (2012) used to determine representative U.S.-DRY and U.S.-WET climate outcomes for the IGSM-WRS projections. The maps present June-August (JJA) averages. Frames a) and c) provide the relative shifts in surface-air temperature (relative to zonal mean temperature) that occur per unit change in global temperature. Frames b) and d) show the relative shifts in precipitation (with respect to the zonal mean).

To explore the relative influence on water requirements of the economic effect of policy (L1S and UCE) vs. the climatic effect, we also project water resources under a scenario of no climate change. For this case, labeled ‘NoCC’, we assume that the climate is similar to the 20th century. We use data from a run of the IGSM driven by historical greenhouse gas concentrations. In this experimental exercise, we assume that water resources are influenced by the socioeconomic scenarios L1S and UCE, but that the climate is stationary.

6.1 Water Requirements

Water requirements for each sector are projected following the methodology described in Section 4. To calculate requirements for the thermoelectric cooling, public supply, self-supply and mining sectors, WRS-US requires predictions of population, total GDP and value added of the mining sector. These inputs are predicted by the USREP model (Rausch *et al.*, 2010) under the two emission scenarios described above. As shown in **Figure 9**, population is projected to increase steadily over the period 2005 to 2050 with no difference between the UCE and L1S scenarios. Differences between scenarios are predicted for total GDP, with larger increases under the UCE scenario than under L1S. These differences are represented by USREP region in **Figure 10** for 2050, which again shows that, in total, GDP is projected to be larger under the UCE scenario than under the L1S scenario, especially in Texas. Predictions for value added in the mining sector differ, especially under the L1S scenario, where it is expected to decrease by 2050. Reduced mining activities (especially coal mining) under the constrained GHG emissions scenario explains this trend. These population, GDP, and value added predictions from USREP are combined with econometric estimates described Appendix B to project future water requirements.

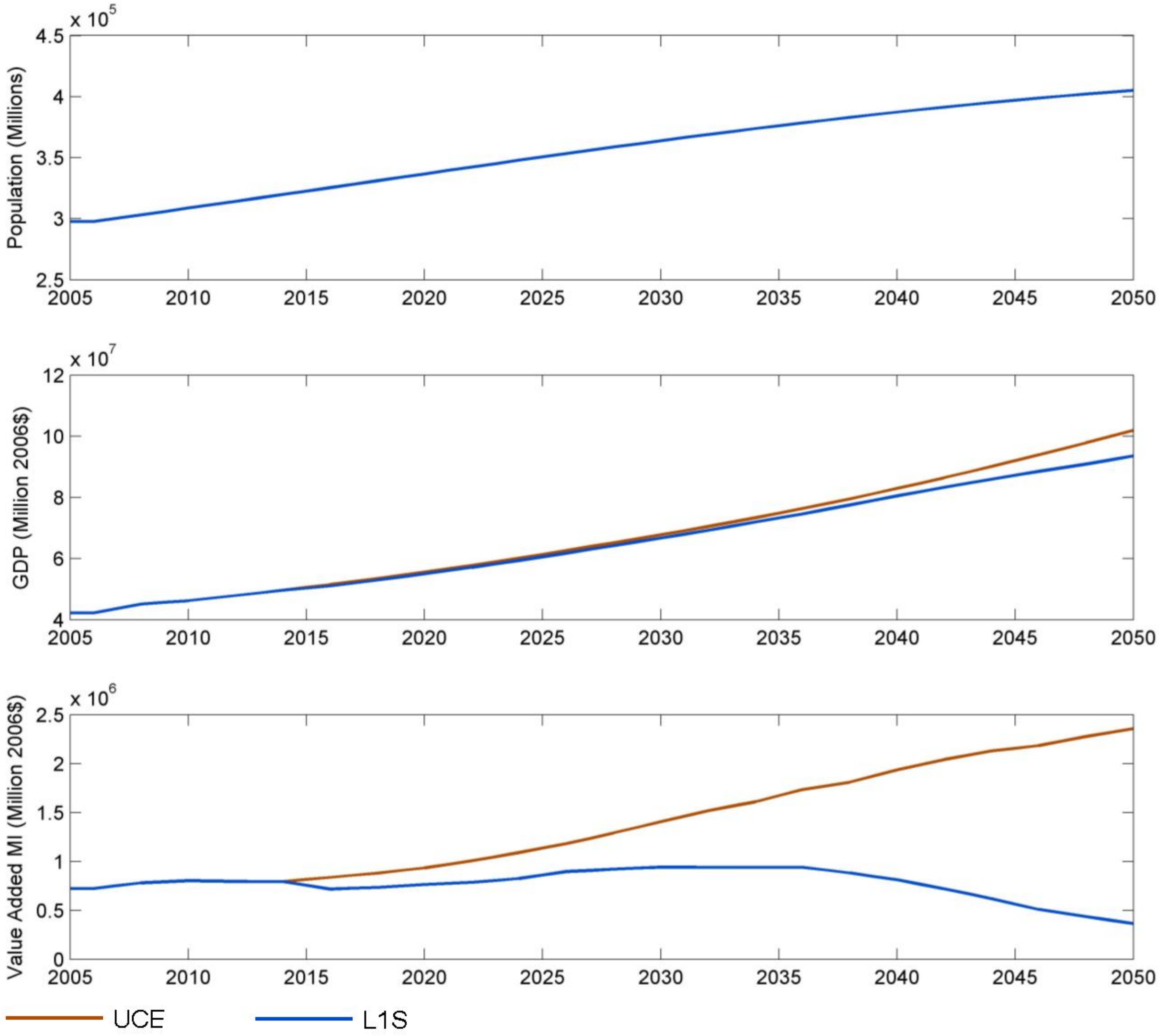

Figure 9. Total population (in Million people), total GDP and Mining GDP (in million 2006USD).

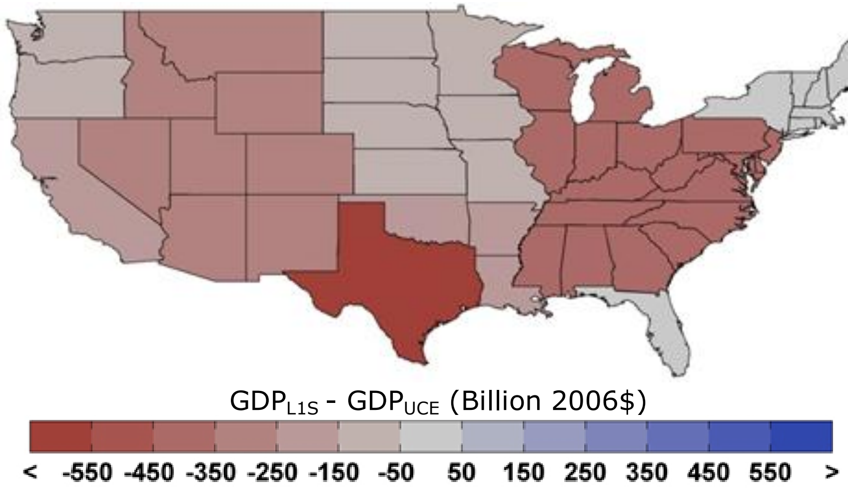

Figure 10. Difference in GDP (in billion 2006USD) between L1S and UCE scenarios in 2050.

As noted in Section 4.2, irrigation water requirements are projected using the CliCrop model. In this study, we assume that there will be no change in the location and amount of irrigated cropland. This condition can be relaxed in subsequent model development as farmers will likely increase production to meet increasing food demand. These increases will likely be achieved in part by cropland expansion, relocation of cropland to more suitable areas, and increases in irrigation.

The projection of U.S. water requirements from 2005 to mid-century is presented in **Figure 11** for each sector and in total. Requirements increase for all sectors under the UCE scenario. Under the L1S scenario, however, water requirements decrease overall for thermal cooling and mining, which reflects a change in energy production due to a slower pace of economic growth and a transition to cleaner energy. Beyond 2030, significant shares of electricity are predicted to be generated from renewables, and as a result, electricity from coal is gradually reduced and disappears beyond 2030. Water requirements for irrigation are driven indirectly through the effect of the different policy scenarios on climate. Figure 11 shows some increases in irrigation water requirements over time, especially under the UCE scenario. Under the scenario of no climate change, irrigation requirements are expected to decrease. Water requirements for self-service are expected to grow steadily. For public supply, however, we observe a non-linear trend reflecting the fact that the effect of a higher requirement is offset by greater water use efficiency as GDP per capita increases. In total, water requirements are projected to increase with the largest increases in water requirements being projected under the UCE scenario.

Total water requirements at the ASR level are provided in **Figure 12** to **Figure 17**. In these figures, we first present water requirements in quantitative terms for the base period (2005–2009) and then show for the projection period (2041–2050) the changes relative to the base period (in %) under the two scenarios and three climate patterns. **Figure 12** shows that the largest water requirements in the base period originate from the Upper/Central Snake (ASR 1703) and San Joaquin-Tulare (ASR 1803) basins. In the period 2041 to 2050 total water requirements are projected to increase by more than 300% in the Little Colorado (ASR 1501), Lower Rio Grande (ASR 1305) and Richelieu (ASR 106) basins.

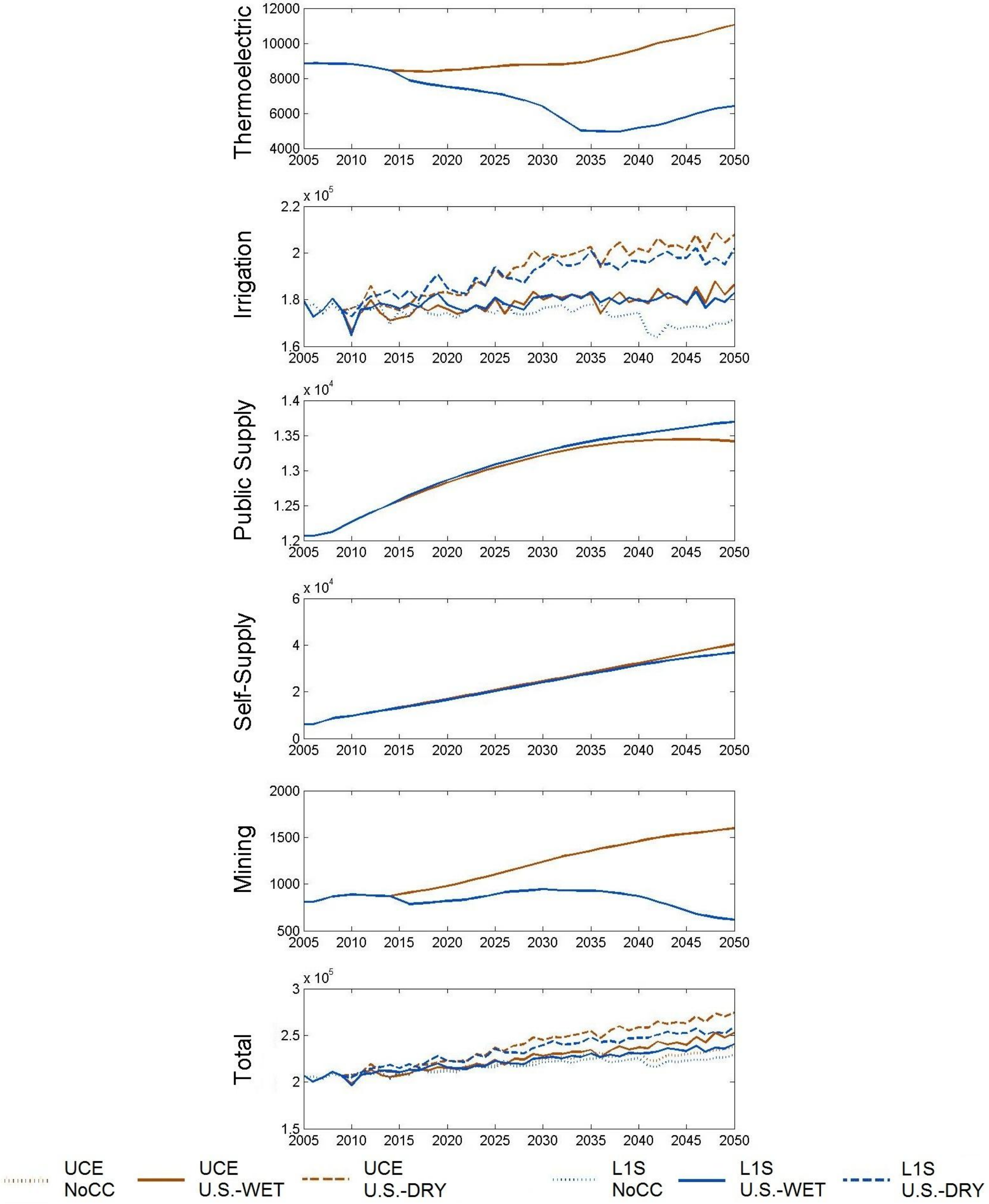

Figure 11. U.S water requirements (in MCM), from 2005 to 2050.

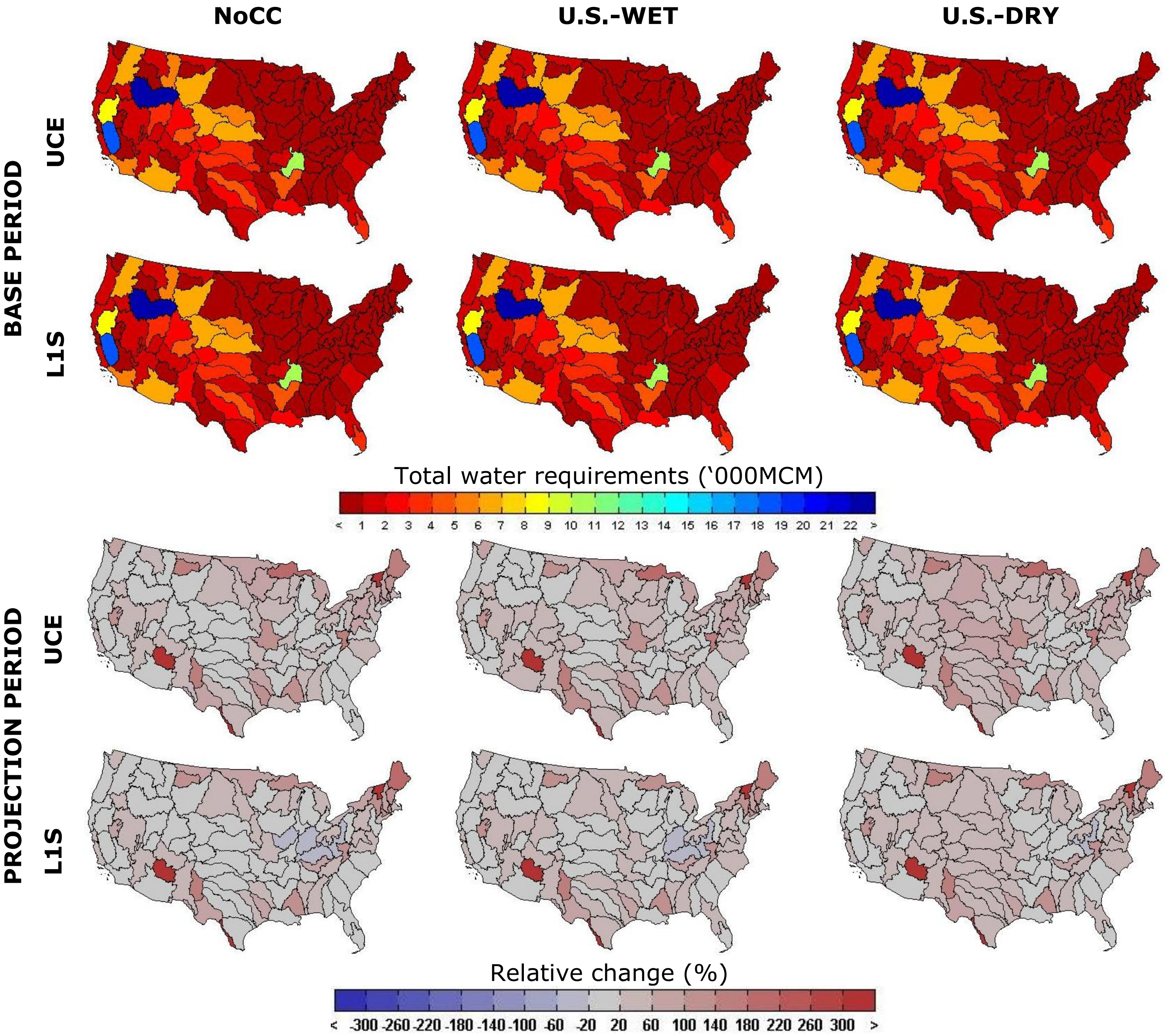

Figure 12. Total water requirement (in '000MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050).

Increases are generally slightly lower under the L1S scenario than under the UCE scenario. Slight regional divergences across scenarios are projected in the Indiana/West Virginia region with decreases in water requirements projected under the L1S scenario. Similarly to what is observed in Figure 11, total water requirement increases are projected to be the largest under the U.S.-DRY climate change pattern.

To further explore the origin of these changes in total requirements, we provide detailed regional representations for each sector. Requirements for thermoelectric cooling are presented in **Figure 13**. Projections for this sector do not vary by climate pattern as there is not feedback from climate onto the economics that drive these requirements. In the base period, requirements for thermoelectric cooling are the largest in the Eastern part of the country, and especially in the Upper Ohio-Big Sandy (ASR 502) basin. In the Northeastern part of the country, large increases (>200%) are projected under both scenarios. However, in absolute terms, these changes are relatively small. Under the L1S scenario, water requirements are mostly expected to decrease. Alternatively, water requirements for thermoelectric cooling are generally projected to increase under the UCE scenario, especially in the South Central part of the country where the largest absolute increase is projected in the Lower Mississippi region. These differences in water requirement reflect a change toward cleaner, non-thermoelectric power generation sources under a GHG emission mitigation scenario (L1S) compared to an increasing reliance on this generation to meet growth in energy need under an unconstrained emission policy (UCE).

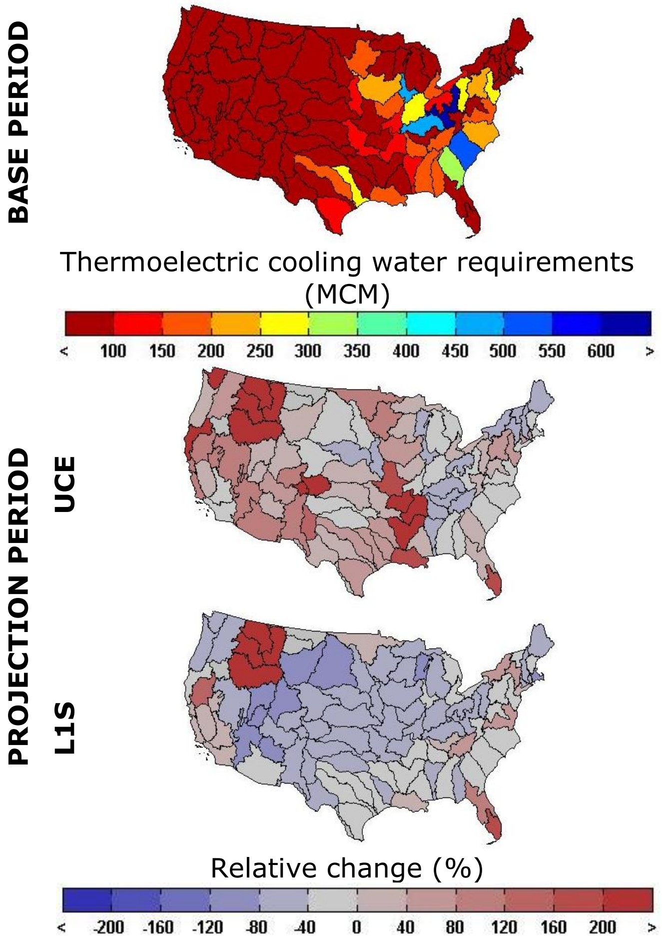

Figure 13. Thermoelectric cooling water requirement (in '000MCM) for the base period (2005––2009) and relative change (in %) for the projection period (2041–2050).

Irrigation water requirements are represented in Figure 14. The top map shows that the largest irrigation water users are the Upper/Central Snake (ASR 1703) and San Joaquin-Tulare (ASR

1803) basins. Very little water is used for irrigation in the eastern part of the country due to high precipitation and relatively low evaporative demand. Water requirements for irrigation purposes are expected to increase in the western part of the country under both climate change patterns. Depending on the climate pattern considered, however, irrigation water requirements differ in the North-Central part of the U.S., with decreases projected under the U.S.-WET climate pattern and increases under the U.S.-DRY climate pattern.

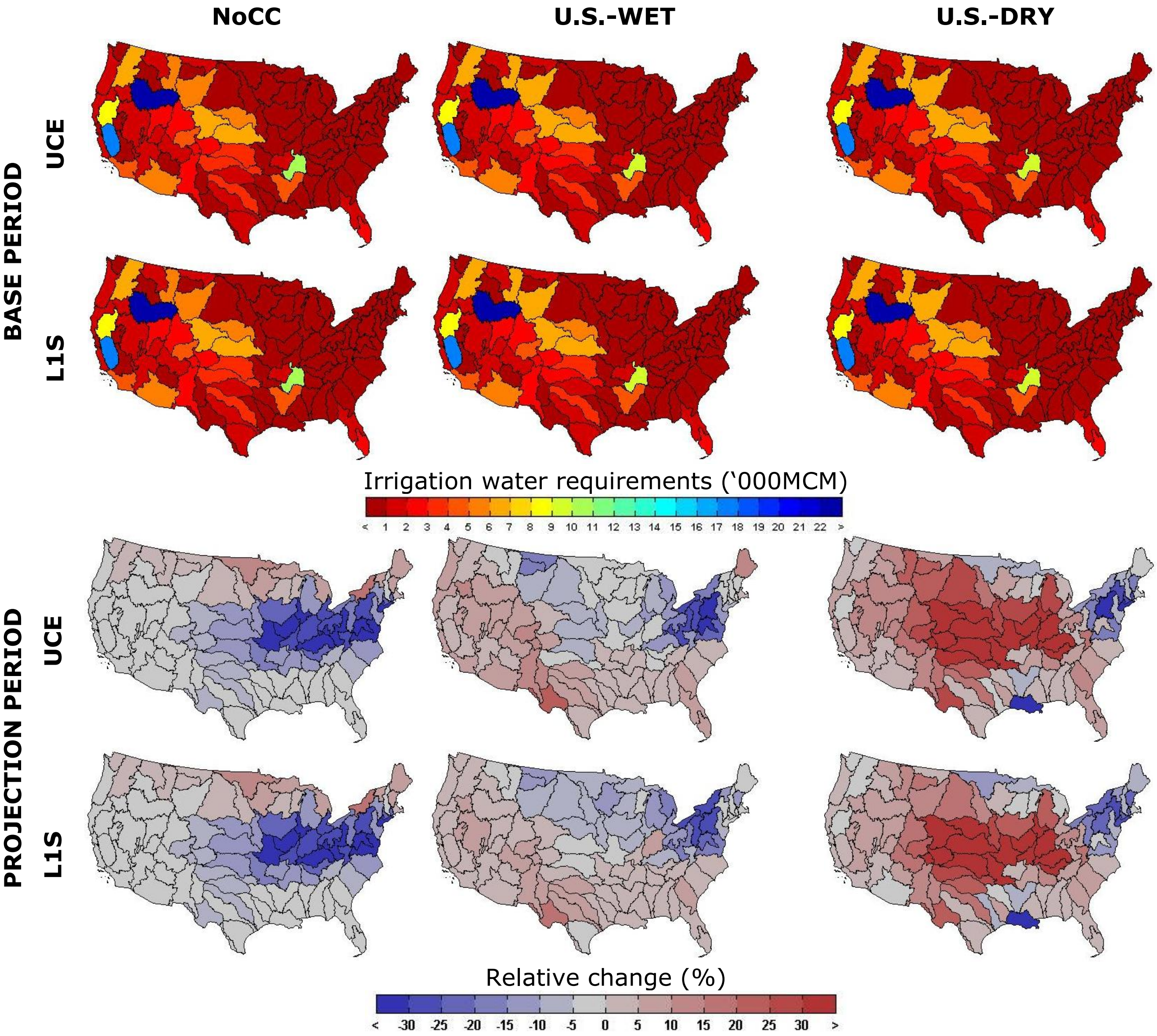

Figure 14. Irrigation water requirement (in '000MCM) for the base period (2005-2009) and relative change (in %) for the projection period (2041-2050).

The NoCC climate pattern projects water requirement increases along the Canadian border. All climate patterns show a decrease in irrigation water requirements in the Northeast.

Public supply requirements are presented in **Figure 15**, which shows that the higher requirements originate in the South, especially in the densely populated Southern California (ASR 1806) and Trinity-Galveston Bay (ASR 1202) basins. Public supply water requirements are expected to increase in the Mountain and Southwest regions with little divergence across scenarios.

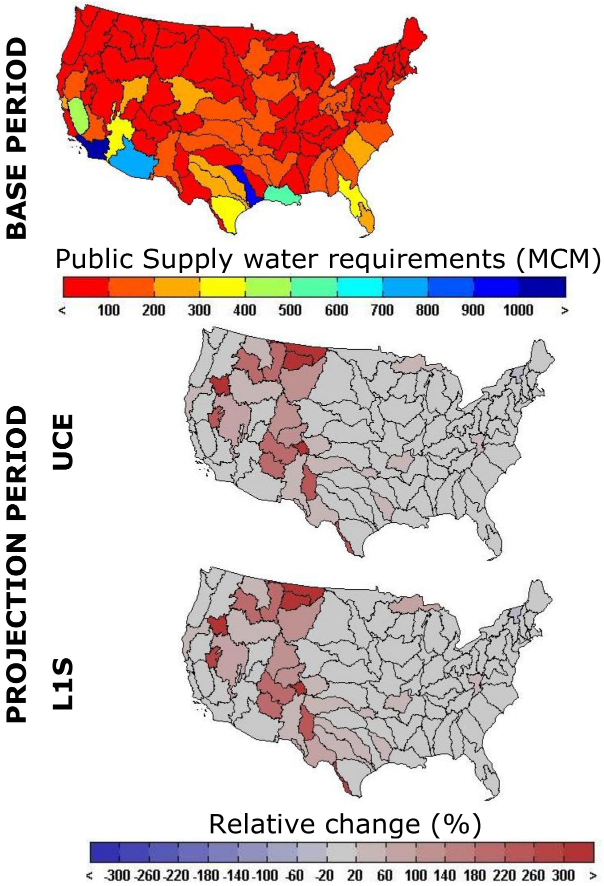

Figure 15. Public Supply water requirement (in MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050).

Self-Supply requirements, represented in **Figure 16**, are the largest in the Mississippi Delta (ASR 803) and Trinity-Galveston Bay (ASR 1202) basins. These requirements are expected to increase substantially under both scenarios over most of the U.S. Only a few basins in the Western and the Eastern parts of the country will require less than double the water supply compared to the base period.

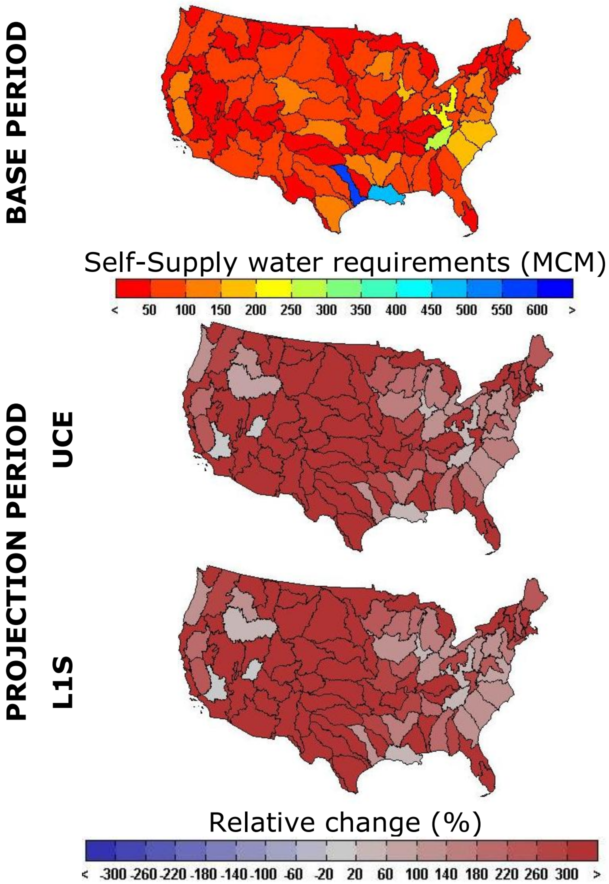

Figure 16. Self-Supply water requirement (in MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050).

Mining water requirements, which represent less than 1% of total water withdrawals in the U.S., are widely spread geographically. Figure 17 shows that the largest water requirements for mining purposes are in the Lake Superior (ASR 401) basin. Mining water requirement are expected to generally increase under the UCE scenario but decrease under the L1S scenario. However, in the South East, and especially in Tennessee, water requirements for mining are projected to increase under both scenarios.

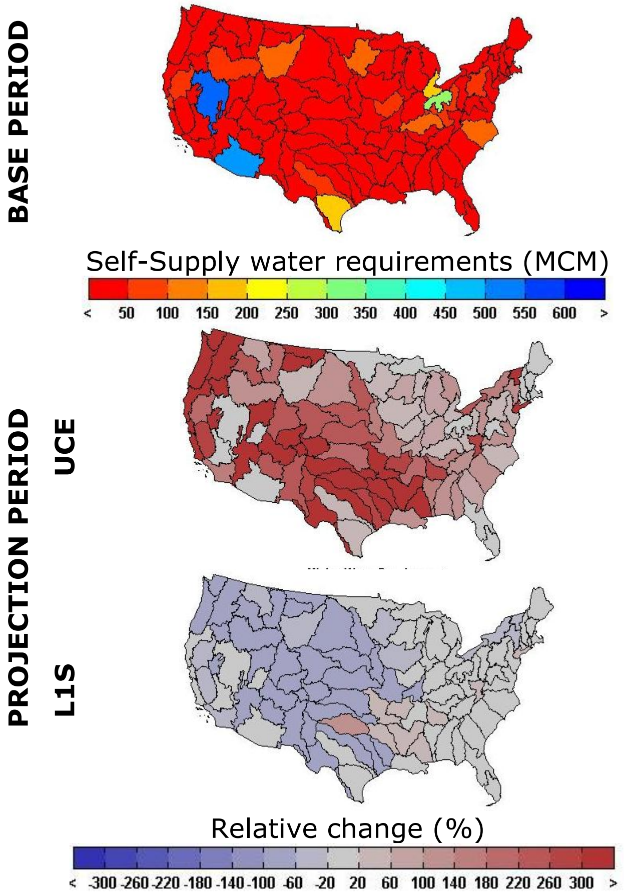

Figure 17. Mining water requirement (in MCM) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050).

6.2 Natural Runoff

As described in Section 3, runoff is projected using bias-corrected estimates from CLM under the two policy scenarios and three climate patterns. Total natural runoff (not including inflows from upstream basins) is presented in **Figure 18**. It is projected to slightly increase toward the mid-century in all cases but to be generally lower under the L1S than under the UCE scenario. For each policy, the projected runoff is very similar for the two climate change patterns (wet vs. dry). Runoff under the NoCC climate pattern has slightly different inter-annual variations.

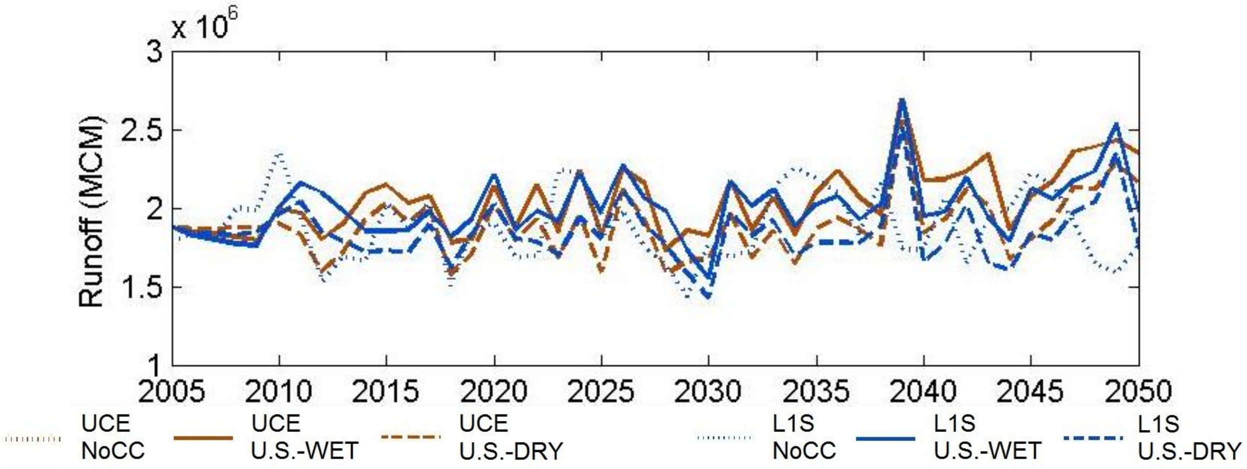

Figure 18. Total natural runoff (in MCM) and from 2005 to 2050.

A geographical representation of natural runoff, provided in **Figure 19**, shows absolute values for the base period (2005–2009) and percentage changes for the projection period (2041–2050). The figure shows large spatial discrepancies at the regional level. In the Southwest, where runoff is relatively small in the base period, runoff is projected to slightly decrease under all climate patterns. In the U.S.-WET case, however, some increases are projected in some of these Southwest basins as well as in most other basins of the country. In the U.S.-DRY case, large decreases in runoff are predicted over most of the West.

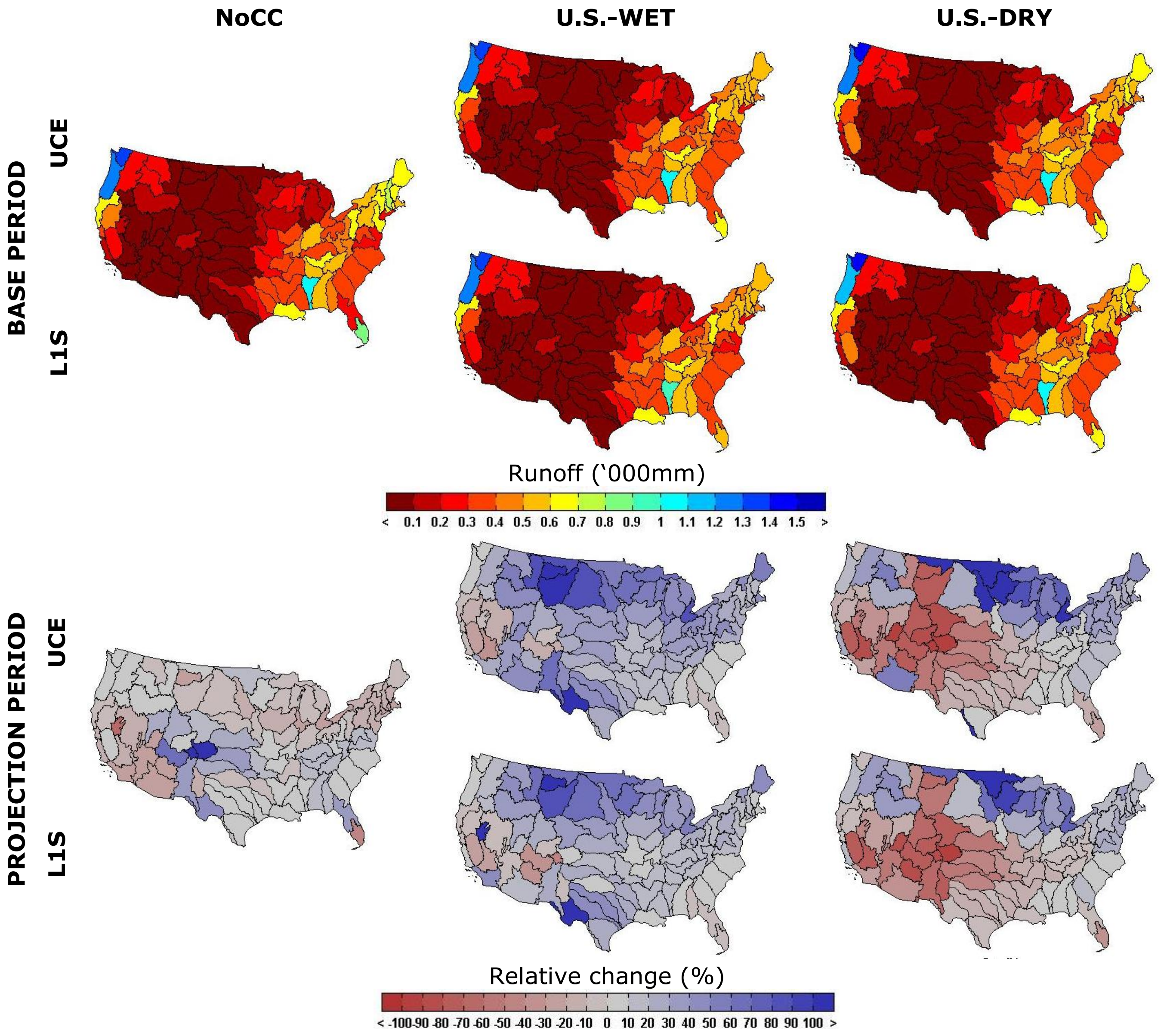

Figure 19. Average annual natural runoff (in ‘000mm) for the base period (2005–2009) and relative change (in %) for the projection period (2041–2050).

As mentioned earlier, groundwater supplies and inter-basin transfers are constrained to their 2005 levels.

6.3 Water Stress

Using the sectoral water requirements and water resources estimates presented above, we then estimate water stress. Numerous indexes have been developed to measure water stress (Brown and Matlock, 2011). In this study, it is estimated using two indicators: the water Supply-Requirement Ratio (SRR) and the Water Stress Index (WSI).

6.3.1 Supply-Requirement Ratio (SRR)

Using the sectoral water requirements and runoff estimates presented above, WRS-US determines water supply for each basin by allocating water to sectors while minimizing water stress across the year (for details see Strzepek *et al.*, 2012b). One of the outputs of WRS-US is the SRR. It is calculated monthly as the ratio of total water supplied over total water required for each sector.[11] This water stress indicator is used to represent physical constraints on anthropogenic water use. Projections of SRR from 2005 to 2050 are presented in **Figure 20** as an annual average for all ASRs weighted by their sectoral water requirements. The figure shows that water stress is generally increasing (as the average SRR decreases) under all climate patterns, and especially under the U.S.-DRY climate pattern. The water stress is slightly smaller under stringent greenhouse gas controls.

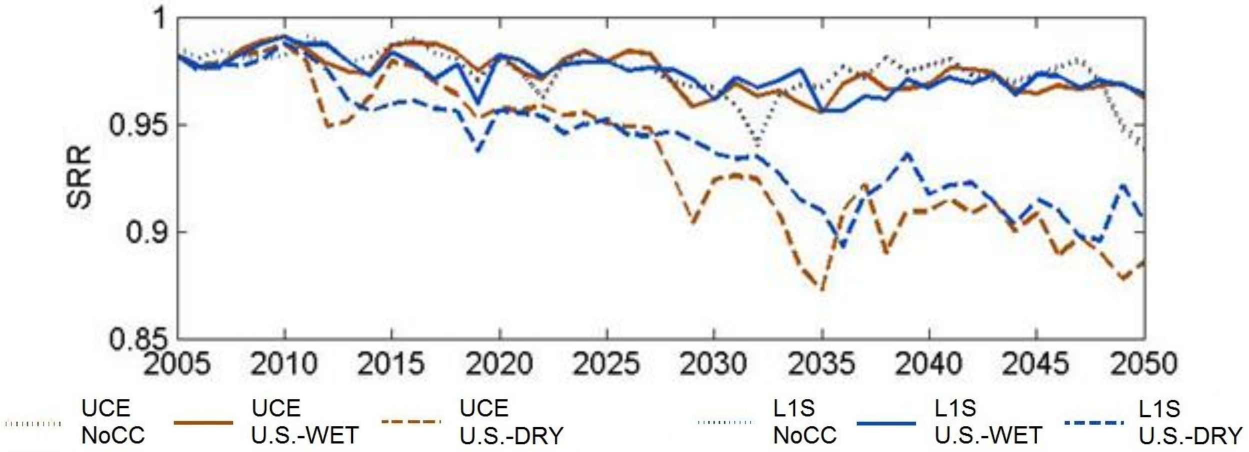

Figure 20. Weighted average over all ARS of the mean annual Depletion-Requirements Ratio (SRR) from 2005 to 2050.

A representation of SRR by ASR is given in **Figure 21**. The map indicates that the SRR is generally close to 1.0 in the base period, indicating that most water requirements are met. Water stress is observed in only four basins: Gila (ASR 1503), Sevier Lake (ASR 1602), Rio Grande Headwaters (ASR 1301) and Upper Arkansas (ASR 1102). In the projection period, the SRR is projected to decrease (or remain constant) in all cases, except in the Rio Grande Headwaters (ASR 1301) basin under the NoCC climate pattern. The largest decreases in SRR (i.e. increases in water scarcity) are projected in the Little Colorado (ASR 1501) basin where water requirements are mainly self-supplied. In the U.S.-DRY case, the decrease in SRR spread further to the North and shows larger reductions overall.

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[11] Water supply is the amount of water supplied to all sectors to meet water requirements. This supply is then inferior or equal to water available.

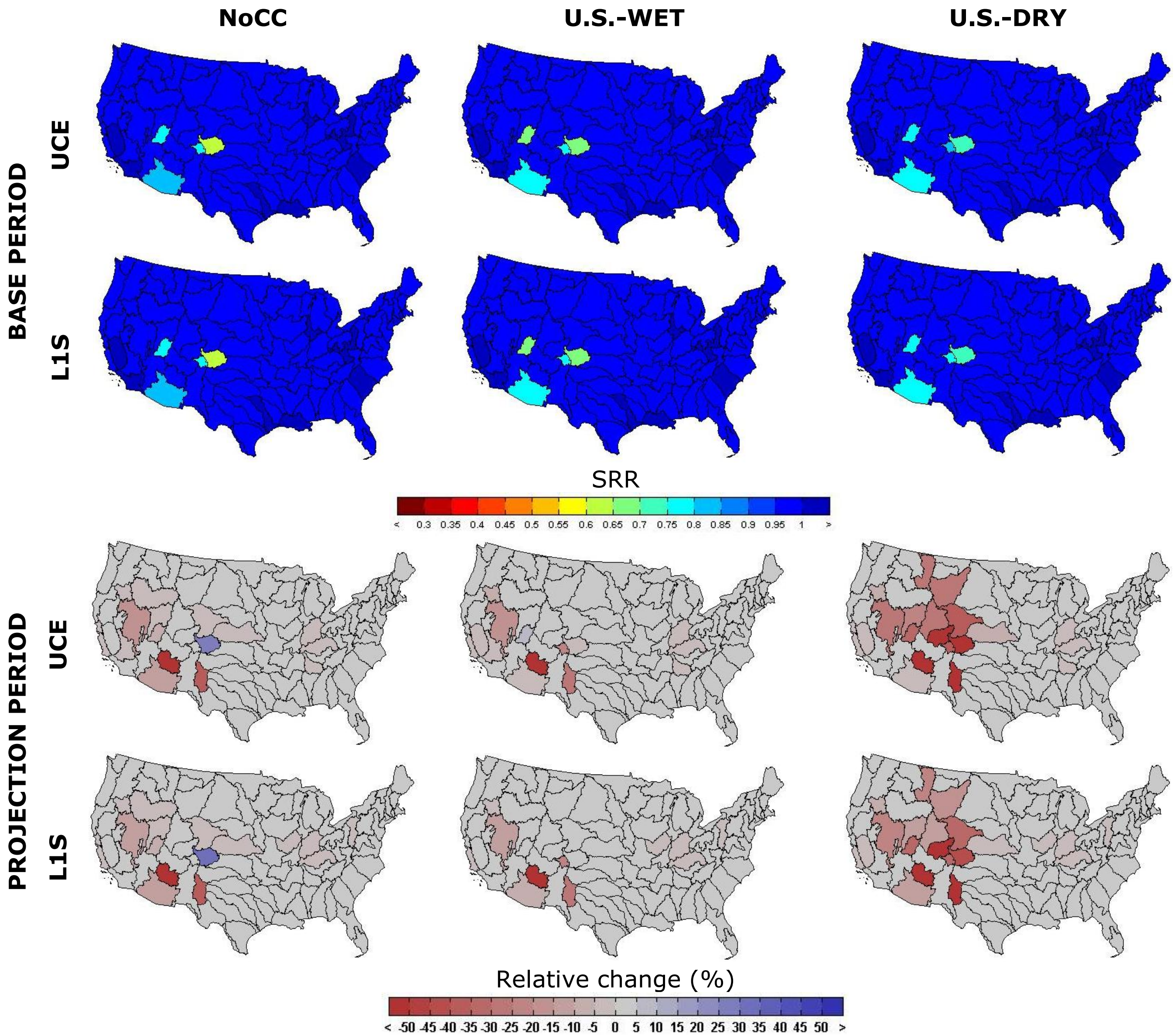

Figure 21. Average Supply-Requirements Ratio (SRR) for the base period (2005–2009) and the projection period (2041–2050).

WRS-US allocates water to irrigation only if there is enough water to meet all other requirements. This means that for some basins affected by water stress, there is very little water available for irrigation. For instance, less than 50% of the irrigation water requirements of the Upper Arkansas (ASR 1102) and Rio Grande Headwaters (ASR 1301) basins can be met in the base period. This water stress is especially important for these basins as irrigation represents more than 95% of the total water requirements.

To isolate the effect of GHG emissions mitigation policies on water stress we calculate the difference between the average annual SRRs in 2050 (SRR_{L1S} minus SRR_{UCE}) for each climate pattern. The blue colored basins presented in **Figure 22** correspond to basins where the SRR under the L1S scenario is higher than under the UCE scenario. For most basins affected by water stress, the climate mitigation policy will be effective at reducing water stress under both climate patterns. However, for several basins, the Gila (ASR 1503), Little Colorado (ASR 1501) and Upper Pecos (ASR 1304) basins, water stress is larger under the L1S scenario than under the UCE scenario in both the U.S.-Dry and U.S.-WET cases. For those basins, climate policies worsen water stress. For the Sevier Lake (ASR 1602) and the Rio Grande Headwaters (ASR 1301) basins, however, the impact of a climate policy on water stress depends on the climate pattern used. In the NoCC case, where policy scenarios affect water requirements but not water resources, the graph shows a unanimous beneficial effect of a reduction in water requirements driven by the L1S scenario.

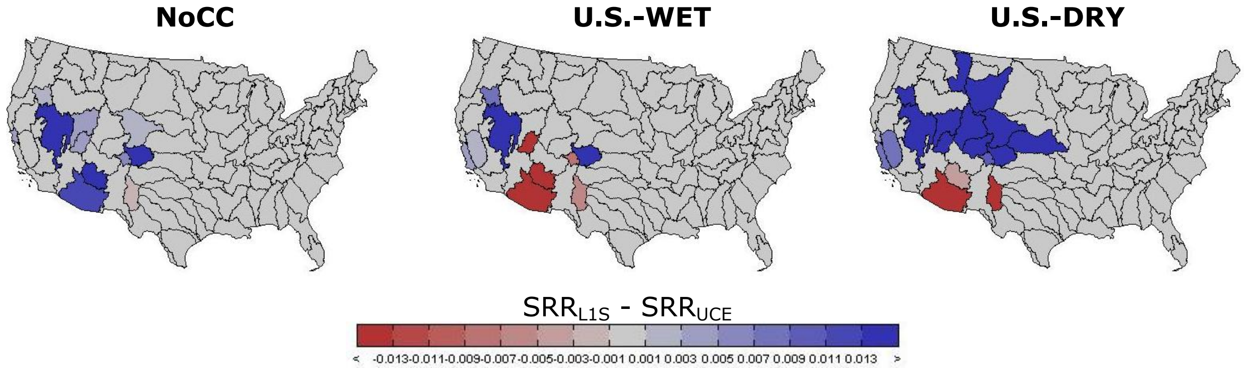

Figure 22. Difference between the average Depletion-Requirements Ratio (SRR) under the L1S and UCE scenarios for each climate pattern in the projection period (2041–2050).

The average number of ASRs affected by monthly water stress (i.e. ASRs where monthly SRR<1) rises from around 5 ASRs (with an average of 6 months of water stress per year) in the base period, to around 7 to 15 ASRs (with an average of 7 months of water stress per year) in the projection period. To focus on the effect of water stress within the year, we provide in **Figure 23** a series of box plots of monthly SRRs for the basins affected by water stress in the prediction period.[12] The boxes represent for each climate pattern and policy scenario, the 25th to 75th percentile of monthly SRRs (for 2041 to 2050). The whiskers represent adjacent values.[13] The figure shows that the spread of the SRRs (i.e. water stress variability) is larger under the U.S.-DRY case for all basins except the Upper Pecos (ASR 1304) basin. For this basin, the plot shows that the water stress is consistently more important under the U.S.-DRY case than under the U.S.-WET case. The boxes for the L1S scenario are generally smaller and closer to one than those for the UCE scenario, which shows that the climate policy is effective at reducing water stress severity and variability.

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[12] Fourteen ASRs are affected by water stress in the projection period: 1002, 1004, 1007, 1102, 1301, 1304, 1401, 1402, 1501, 1503, 1601, 1602, 1603, and 1707. Four other basins are slightly affected by water stress (1010, 1703, 1803, and 1805) but the average monthly SRRs are very close to 1.0 and therefore are not represented in the box plots.

[13] The adjacent values are the most extreme values within 1.5*(upper quartile – lower quartile).

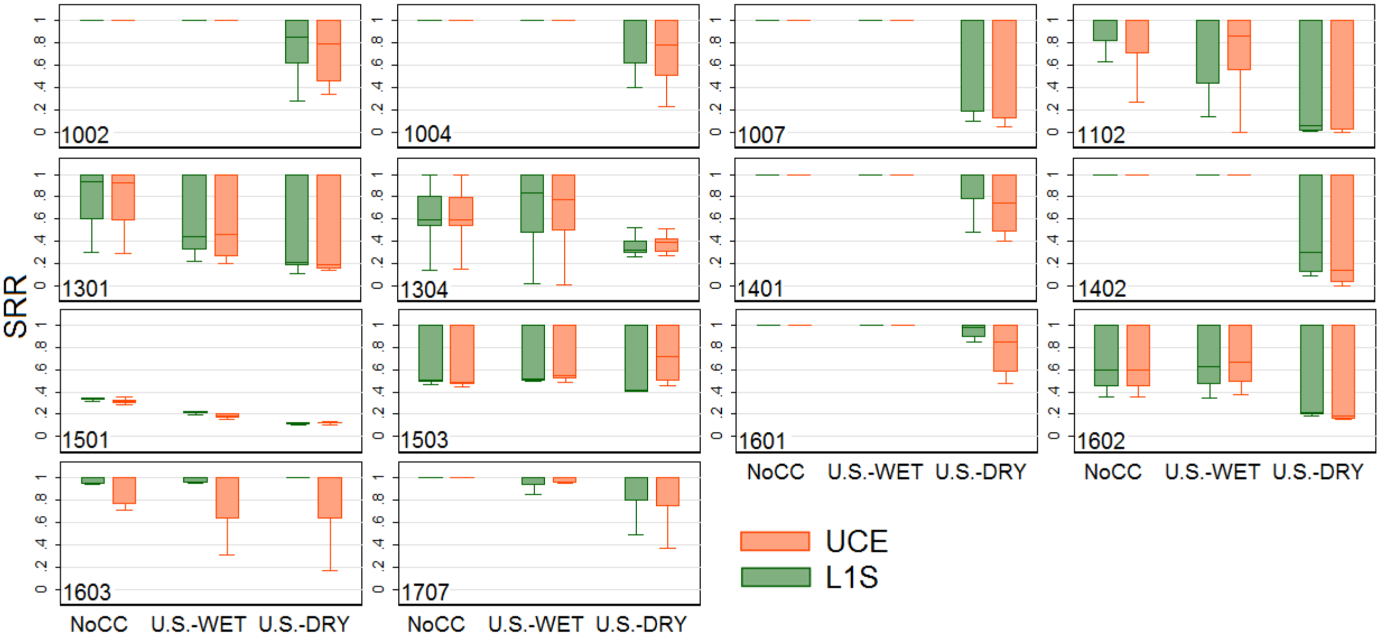

Figure 23. Box plot of the monthly deficit SRRs over all ASRs for the projection period (2041–2050).

Notes: Each box represents, for each climate pattern and scenario, the range of monthly SRRs between the 25th and 75th percentile. The line inside each box represents the median. The whiskers represent adjacent values.

6.3.2 Water Stress Index

Water scarcity can also be estimated using the Water Stress Index developed by Smakhtin *et al.* (2005).[14] This index is used to estimate the pressure human water use exerts on renewable surface fresh water. In this regard, this index is closer to a measure of water reliability. This index is calculated as a ratio of mean annual withdrawals for all sectors (MAW) over mean annual runoff (MAR), while accounting for environmental requirements:

$$WSI = \frac{MAW}{MAR - EWR} \qquad (5)$$

Due to the spatial disaggregation of this study, we account for inflow from upstream basins to estimate total annual runoff. The environmental water requirements are implicitly accounted in the inflows, which are constrained to minimum environmental flows. The severity of water stress is classified as 'slightly exploited' when WSI < 0.3; 'moderately exploited' when 0.3 ≤ WSI ≤ 0.6; 'heavily exploited' when 0.6 ≤ WSI ≤ 1; and 'overexploited' when WSI > 1.

A representation of WSI over all ASRs is presented in **Figure 24**. The figure shows that, in the base period, surface fresh water is generally heavily exploited in the Western U.S. and is overexploited in seven basins. In the prediction period, the changes in WSI are generally increasing in the Central and Western U.S. under the U.S.-DRY climate pattern and decreasing

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[14] Strzepek, et al. (2012) and Schlosser, et al. (2013) use a simpler form of the WSI without EWR in the denominator. The formulation used here is consistent with strong environmental concerns as reflected in U.S. water regulations and other governmental policy actions.

in the Northeast. In the U.S.-WET case, the WSI is projected to decrease generally, except on the coasts. The WSI is projected to increase more uniformly under the NoCC climate pattern.

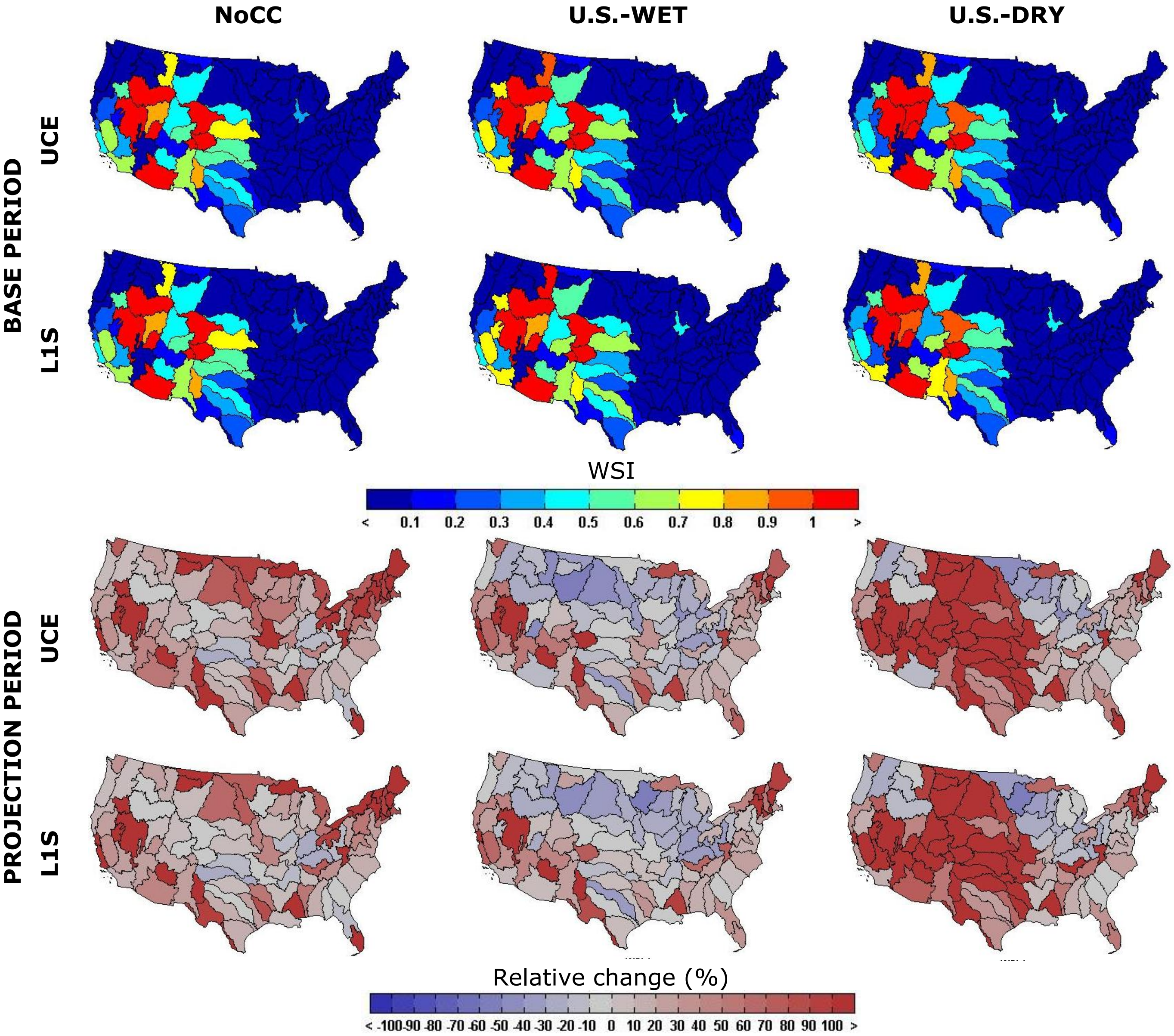

Figure 24. Average Water Stress Index (WSI) for the base period (2005–2009) and the projection period (2041–2050).

This index shows that although most basins will not be affected by unmet water requirements as shown by the SRR ratio, a large number of basins in the West will experience increasing pressure on water resources. This will be especially the case under the U.S.-DRY climate pattern, where over exploited basins are more prone to water shortages.

7. CONCLUSIONS

This paper presents a model of U.S. water resource systems, termed the WRS-US. For this exercise, we downscale the IGSM-WRS model to the 99 ASR level for the continental U.S. We also produce new estimates of water resources and water requirements for five sectors. WRS-US is used to allocate these water resources among the different sectors to minimize water stress, which measures the degree to which water requirements that cannot be met. As an illustration, the model is used to project water stress through 2050 under two climate policies.

We estimate that, with or without climate change, average annual water stress is predicted to increase most in the Southwest. This increase is mostly attributable to increases in water requirements. The study reveals that the choice of climate pattern considered for projections greatly influences the outcome of the model. On average, larger water stresses are projected under the U.S.-DRY climate pattern, than under the U.S.-WET pattern. The impact of a constrained GHG emission policy (L1S scenario) will generally lessen the increase of mean annual water stress, especially in the U.S.-DRY case. However, in some basins water stress will be lower under an unconstrained emission policy (UCE scenario) than under a climate policy. A more detailed analysis of water stress at the monthly level reveals that the extent and intensity of monthly water stress is less under the L1S scenario than under the UCE scenario in most basins. The WSI index, representing the reliability of water resources, shows that, although most basins will not be affected by unmet water requirements in the future (as shown by the SRR ratio), a large number of basins in the West will see increased pressure on water resources, especially under the U.S.-DRY climate pattern.

In developing an integrated model of changes in water supply, climate change, and water use, some simplifications are necessary. The most important of these simulations is the assumption that irrigated areas remain unchanged in the future. In principle, we may see adjustments in areas that are regularly short of water for irrigation because maintenance of irrigation infrastructure may become uneconomic. On the other hand, irrigation may expand in areas where water supplies are ample but crop yields are reduced because of increased droughts. We identify those areas where water stress increases, and where it therefore may become uneconomic to maintain irrigation infrastructure at its current level. Whether losses of food production in these regions would be replaced through dryland or irrigated cropland elsewhere in the U.S. or abroad requires further investigation and modeling. We also assume that current rates of groundwater withdrawal are sustainable. If they are not, either because withdrawal currently exceeds recharge or climate changes in such a way as to reduce recharge, then irrigation dependent on groundwater may cease in these areas with possible increased pressure on surface water flows.

Notwithstanding these simplifications, WRS-US is an important tool for water resource planning and management. It has substantial advantages over other water models in that it is part of an integrated assessment framework, the IGSM. This framework allows integrated assessments of water resources and uses in the context of climate and economic effects; this allows simultaneous treatment of the supply and use sides of the management challenge. The current estimation of climate change also allows the estimation of climate change uncertainty on water resources and ultimately on water stress. The framework will also support the development of feedbacks to assess the implications of water stress on the economy.

This model also represents a significant improvement compared to global water models. First, by focusing on the U.S. we take advantage of water-use data detailed at the county level to estimate and project public supply, self-supply and mining water requirements. Additionally, the WRS-US model includes regional estimates of water for thermoelectric cooling, which are derived from the U.S. specific computable general equilibrium model (USREP). This application also takes advantage of U.S. farm survey data to precisely calibrate irrigation demand. The spatial disaggregation allows the detection of local water issues, such as the water deficit in the West. Future applications could focus on the impact of such water stress on economic activities. Such applications range from investigating water stress impacts on food production, to stream flow level impacts on naval transportation. This downscaled model also lays the foundations for further investigation of water allocation strategies (e.g., a comparative study of different objective functions for water supply), which are not possible at wide river basin delineations.

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APPENDIX A: ASSESSMENT SUB-REGION (ASR) DESCRIPTIONS

NEW ENGLAND REGION
101 Northern Maine
102 Saco-Merrimack
103 Massachusetts-Rhode Island Coastal
104 Housatonic-Thames
105 Connecticut River
106 Richelieu

MID ATLANTIC REGION
201 Upper Hudson
202 Lower Hudson-Long Island-North New Jersey
203 Delaware
204 Susquehanna
205 Upper and Lower Chesapeake
206 Potomac

SOUTH ATLANTIC GULF REGION
301 Roanoke-Cape Fear
302 Pee Dee-Edisto
303 Savannah-St Marys
304 St Johns-Suwannee
305 Southern Florida
306 Apalachicola
307 Alabama-Choctawhatchee
308 Mobile-Tombigdee
309 Pascagoula-Pearl

GREAT LAKES REGION
401 Lake Superior
402 NW Lake Michigan
403 SW Lake Michigan
404 Eastern Lake Michigan
405 Lake Huron
406 St Clair-Western Lake Erie
407 Eastern Lake Erie
408 Lake Ontario

OHIO REGION
501 Ohio Headwaters
502 Upper Ohio-Big Sandy
503 Muckingum-Scioto-Miami
504 Kanawha
505 Kentucky-Licking-Green-Ohio
506 Wabash
507 Cumberland

TENNESSEE REGION
601 Upper Tennessee
602 Lower Tennessee

UPPER MISSISSIPPI REGION
701 Mississippi Headwaters
702 Black-Root-Chippewa-Wisconsin
703 Rock-Mississippi-Des Moines
704 Salt-Sny-Illinois
705 Lower Upper Mississippi

LOWER MISSISSIPPI REGION
801 Hatchie-Mississippi-St Francis
802 Yazoo-Mississippi-Ouchita
803 Mississippi Delta

SOURIS-REO-RAINY REGION
901 Souris-Red-Rainy

MISSOURI REGION
1001 Missouri-Milk-Saskatchewan
1002 Missouri-Marias
1003 Missouri-Musselshell
1004 Yellowstone
1005 Western Dakotas
1006 Eastern Dakotas
1007 North and South Platte
1008 Niobrara-Platte-Loup
1009 Middle Missouri
1010 Kansas
1011 Lower Missouri

ARKANSAS-WHITE RED REGION
1101 Upper White
1102 Upper Arkansas
1103 Arkansas-Cimarron
1104 Lower Arkansas
1105 Canadian
1106 Red-Washita

1107 Red-Sulphur

TEXAS GULF REGION
1201 Sabine-Neches
1202 Trinity-Galveston Bay
1203 Brazos
1204 Colorado (Texas)
1205 Nueces-Texas Coastal

RIO GRANDE REGION
1301 Rio Grande Headwaters
1302 Middle Rio Grande
1303 Rio Grande-Pecos
1304 Upper Pecos
1305 Lower Rio Grande

UPPER COLORADO REGION
1401 Green-White-Yampa
1402 Colorado-Gunnison
1403 Colorado-San Juan

LOWER COLORADO REGION
1501 Little Colorado
1502 Lower Colorado Main Stem
1503 Gila

GREAT BASIN REGION
1601 Bear-Great Salt Lake
1602 Sevier Lake
1603 Humboldt-Tonopah Desert
1604 Central Lahontan

PACIFIC NORTHWEST REGION
1701 Clark Fork-Koontenai
1702 Upper/Middle Columbia
1703 Upper/Central Snake
1704 Lower Snake
1705 Coast-Lower Columbia
1706 Puget Sound
1707 Oregon Closed Basin

CALIFORNIA SOUTH PACIFIC REGION
1801 Klamath-North Coastal
1802 Sacramento-Lahontan
1803 San Joaquin-Tulare
1804 San Francisco Bay
1805 Central California Coast
1806 Southern California
1807 Lahontan-South

APPENDIX B:
PUBLIC SUPPLY (PS), SELF-SUPPLY (SS), AND MINING (MI) ESTIMATION

Water withdrawals for the Public Supply (PS), Self-Supply (SS) and Mining (MI) sectors are estimated using panel data econometric techniques. We use county level data on water withdrawals from USGS (2011). USGS provides water withdrawal data every five years from 1985 until 2005. Water withdrawals are given in Millions of gallons per day (Mgal/d). USGS (2011) also provides population estimates by county. Sectoral and state-level GDP is sourced from the Bureau of Economic Analysis (BEA, 2011).

Data are aggregated at the ASR level. However, there is no water use data available for two river basins (ASR 1602 and 1807). As indicated in Figure 2, these basins are closed and are in sparsely populated regions. We assume that there is no water requirement in these regions.

Water withdrawal for public supply, PS, is specified as:

$$PS = f\,(log(pop), log(GDP/pop), log(GDP/pop)^2) \qquad \text{(B1)}$$

where PS is a function of total population (pop), real gross domestic product per capita.

(GDP/pop) and a square term of GDP/pop to represent non-linear effects. The regression results, provided in Table B1 indicate that as population increase, PS water requirement increases, and that as GDP per capita grows, households become more environmentally conscious and reduce water use. The square term, however, represent a concave relationship and indicate that the marginal decrease in water requirement due to an increase in GDP per capita diminishes as the economy develops.

Self-supply water requirement is specified as a function GDP for all sectors except Mining and its square term:

$$SS = f\,(log(GDP_{noMI}), log(GDP_{noMI})^2) \qquad \text{(B2)}$$

The estimated relationship, also presented in Table B1, shows that as GDP grows, water requirement increases, but the marginal increase becomes smaller as the agents become more efficient in their water use.

Water withdrawals for mining purposes are estimated as a function of mining GDP and its square term:

$$MI = f\,(log(GDP_{MI}), log(GDP_{MI})^2) \qquad \text{(B3)}$$

GDP has a non-linear effect on MI water withdrawal similar to that estimated for SS. As GDP grows, water requirement increases, but the marginal increases become smaller as mines become more efficient in their water use.

Water withdrawals for these sectors are estimated using the xtscc panel estimator. This panel estimator is preferred as it provides Driscoll-Kraay standard errors which are robust to very wide forms of temporal and cross-sectional correlation. River basin fixed effects are included to account for unobserved characteristics that vary across basins but not over time.

Table B1. water withdrawals regression results.

VARIABLES	PS	SS	MI
Log(Population)	221.2***		
	(5.103)		
Log(Real GDP per capita)	-116.6***		
	(6.755)		
Log(Real GDP per capita)^2	17.79***		
	(0.463)		
Log(Real non-Mining GDP)		1,456***	
		(136.1)	
Log(Real non-Mining GDP)^2		-57.69***	
		(5.721)	
Log(Real Mining GDP)			24.67**
			(10.35)
Log(Real Mining GDP)^2			-1.774*
			(0.913)
Observations	422	422	370
R-squared	0.957	0.882	0.818
Number of groups	99	99	98

Notes: dependent variable is annual water withdrawal in Mgal/day for each sector. Standard errors in parentheses; significance levels: *** p<0.01, ** p<0.05, * p<0.

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