Climate Change, Migration, and Water Shortage

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Abstract: Future climate change will likely to increase the frequency and severity of droughts in many regions of the U.S., especially in the southwestern states, thus further will reduce the water supply in those states. On the water demand side, the population of the U.S. also moves to the southwestern states (both domestic and international migrants). Coupling the projections of water supply and demand, we generate the relative water stress index for the contiguous U.S. counties for the years 2020, 2030, 2040, and 2050. We find a worsening water stress situation, especially in the western U.S. Meanwhile, we find that some metropolitan areas in the east may also have severe water stress despite good water supply.

Key words: Climate change, water supply and demand, human migration

INTRODUCTION

Climate change, such as changes in temperature and precipitation, are expected to affect future water supply. An unstable water supply may have impacts on other socio-economic conditions, such as living quality, agricultural and industrial production, and so on. According to the U.S. Drought Monitor map (Figure 1), drought is already a severe issue in many regions of the U.S., especially in the southwestern states. But the future water stress could be more severe in the western U.S., due to “future projections for less total annual rainfall, less snowpack in the mountains, and earlier snowmelt” (CCSP, 2008). Seager et al. (2013) also predicted that water supplies would decrease in the southwestern states, by comparing the period of 2021-2040 to 1951-2000. Overall, future climate projections in the U.S. are expected to cause a water supply trend that the wet will get wetter and the dry will get drier (Melillo et al., 2014).

On the demand side, the recent water demand has been relatively stable for the U.S. since 1985 (Kenny et al., 2009), as increases in efficiency may offset water stress from population growth and economic development. However, efficiency may decrease in some economic sectors in the future. For instance, higher temperature and lower precipitation are likely to increase irrigation water demand in agricultural production. Future population movement may also cause water stress in some regions – most migrants moving to the U.S. go to the southwestern states. For instance, about 70% of Mexican born population resided in just four states – California, Texas, Illinois, and Arizona (Terrazas, 2010). However, this trend is expected to continue in the near future, as the U.S. looks for more Mexican migrants due to labor shortage (O’Neil, 2013). Furthermore, the U.S. population has a long term trend of moving from the northeast to the southwest, thus the population in the southwestern states are expected to increase faster than the rest of the country. These new domestic and international migrants will increase the water demand, worsening the already severe water shortage in the southwestern states. Furthermore, it has been found that climate change in other countries, such as Mexico, may drive additional migrants into the U.S. (Feng et al., 2010; Feng and Oppenheimer, 2012; Cai et al., 2014). Therefore, global warming may exacerbate the water issue from both supply and demand perspectives.

Overall, in the near future, we are expecting the lower water supply and higher water demand in the southwestern states, and thus a severe water stress. This could have severe impacts on the regional socio-economic conditions, and pose challenge to local policymakers in managing water resources. There are likely to be several competitions for water resources. For instance, competitions between new-coming immigrants and the residents may rise. Also, there are likely to be tight competitions among different economic sectors, such as agriculture and other industry sectors.

Policymakers in the southwestern states need to implement new policies in order to adapt to the rising water stress that is complicated by the changes from both supply and demand side. While future water stress is generally expected for the southwestern states, which regions will experience more severe stress is still unknown. For instance, for the state of Oklahoma, the overall water supply is sufficient, but the water is not where it is needed, thus the water stress varies geographically. For other regions of the southwestern states, the water stress is also spatially heterogeneous. Therefore, localized water stress projections could be useful information for policymakers to better manage the water resources.

Frederick and Major (1997) has reviewed the literature related to the impacts of climate change on the U.S. water supplies, which has been extensively studied. Usually, a hydrologic model is implemented to aid the water supply projection. A popular example is the Distributed

Hydrology Soil Vegetation Model (DHSVM), originally developed by Wigmosta et al. (1994), which "explicitly represents the effects of topography and vegetation on water fluxes through the landscape".

Compared to the water supply, relatively less work has been done to investigate the water demand. Excluding the water demand from water stress estimation may underestimate the future water scarcity and miscalculate the location of severe water stress. Less previous work in water demand may be due to its complexity in addressing how the regional socio-economic conditions may affect the water use. Brown (1999) estimated the U.S. water use to the year 2040. The projections are made by extending past trends of major water use determinants, such as population and income. Assuming the future improvements in water use efficiency, Brown (1999) projected that the water demand for the U.S. during 2000-2040 may fall below 10% of the 1995 level, despite larger population. The projection also showed regional variations in water demand. However, Brown (1999)'s research did not include water supply, thus could not illustrate the actual water stress. Tetra Tech (2010) conducted a more comprehensive analysis by combining water supply projections based on several climate models, and water demand projections mainly based on the current population growth trend. They concluded that climate change will increase the number of areas with water supply less than expected water withdrawal.

In this study, we generate forecasts for the relative water stress for the contiguous U.S. counties to the year 2050 as compared to a current baseline year, incorporating both the projections in water supply due to global warming and water demand due to population growth, including both natural population growth and immigration (from both domestic and international migration). We illustrate the relative water stress at the county level, so that local policymakers will have better information about how the future water stress will change regionally – more severe or less severe. While it is not hard to tell that the water stress in general will be more severe in the near future in the U.S., this study serves two purposes: first, quantifying the relative water stress; second, illustrating a spatially explicit relative water stress.

In specific, we assume that the water supply just fulfill demand for all the contiguous U.S. counties in the baseline year 2016.[1] Starting from that year, we project the county-level water supply until year 2050 based on the water supply projections from Milly et al. (2005 and 2008), which are generated from an ensemble 12 climate models. For the water demand, we predict the future population to the year 2050, assuming that water demand will grow linearly with the size of population. While the water demand in agricultural sector may not be affected by local population immediately in the short term, we believe that it will be affected in the long term as more people needs more food. Thus, for the purpose of simplicity, we assume that the total water consumption (from urban use, agriculture, and industries) expand in the same rate as population growth. Thus we implicitly assume that per capita water demand will not change due to economic and technological development. Whether per capita water use will increase or decrease depends on the future water use efficiency and agricultural/industrial production. Brown (1999) assumed the continuously improving water use efficiency in the future, while we expect that a higher agricultural irrigation water demand due to higher temperature and lower precipitation is likely to reduce water use per output. Given that agricultural/industrial production will increase in the future, we estimate a lower bound of future relative water stress in this paper.

[1] We set the year 2016 as the baseline year, since Milly et al. (2005)'s water supply projections are the changes in 2016-2084 as compared to the average during 1900-1970. To develop a water stress that shows the changes from current level, we use the year 2016 as the baseline year.

By coupling the projections of water supply and demand, we generate a relative water stress index for the U.S. counties for the years 2020, 2030, 2040, and 2050. The relative water stress index shows how the relative ratios of water demand and supply change from a baseline year level.

The rest of the paper proceeds as follows. The next section describes the methods and data that we used for the water supply and demand projections. Then we present the result of a relative water stress map. Then the final section concludes.

METHODS AND DATA

Water supply

In this paper, we use the global water runoff projections from Milly et al. (2005), which are based on an ensemble 12 climate models, including CCSM3, CGCM3.1(T63), ECHAM5/MPI-OM, ECHO-G, FGOALS-g1.0, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, MIROC3.2(hires), MRI-CGCM2.3.2, UKMO-HadCM3 and UKMO-HadGEM1, under the A1B SRES scenario. Milly et al. (2005) predicted globally the percentage change of water availability for the period of 2016-2084, as compared to the 1900-1970 average, assuming that it will only affected by climate change. However, the resolution of their projection is 2.5 degrees in longitude and 2 degrees in latitude, which is larger than most of the U.S. counties.[2] We thus downscale their projections to the county level. If a county is completely located within a 2.5 degrees by 2 degrees grid, the water supply projection of that grid is assigned to this county. For

[2] The western U.S. counties are relatively larger than the eastern U.S. counties. Since our focus is in the southwestern states. The coarse projection provided by Milly et al. (2005) is not a big issue in our study.

a county spread over two or more grids, the area-weighted value of water supply will be calculated using the following equation:

$$Water_{i,t} = \frac{\sum_{j=1}^{n} Gridwater_{j,t} * Fraction_j}{\sum_{j=1}^{n} Fraction_j} \quad (1)$$

where $Water_{i,t}$ represents the water supply for the county *i* in year *t*, $Gridwater_{i,t}$ represents the water supply for the grid *j* in year t. *n* is the number of grids that a particular county covers. $Fraction_k$ represents the fraction of the grid *j* that is occupied by the county *i*. Although the water supply projection is available through the year 2084, we limit our time horizon to the year 2050, as the reliability of forecasts based on climate models and hydrologic models will largely decrease in the long term.

Water demand

In this study, we assume that regional water demand grows linearly with population growth, implicitly assuming that the per capita water usage does not change over time. We can use the following equation to calculate the population change at the county level:

$$Population\ Growth = Birth\ rate + Death\ rate + Net\ domestic\ migration + Net\ international\ migration \quad (2)$$

The following steps show how each of these four components in Equation (2) is estimated in our analysis:

1. *Birth and death rate*: we first calculate the average birth and death rate for the period of 2000-2010 at the county level. These annual data are obtained from the United States Census Bureau. Then we use the 2012 National Population Projections, which includes the national projected birth and death rate 2012-2060, to adjust the county level average

birth rate for 2000-2010 so that we have the birth rate projections for 2012-2060 at the county level. While doing this adjustment, we keep the relative birth rate between any two counties constant.

2. *Net domestic migration*: we calculate the domestic migration rate for each county for the period of 2000-2010, and assume such rate will be the same during the period of 2016-2050. It should be noted that we remove the data from the year 2005 and 2006 as outliers, when the hurricane Katrina hit Louisiana, which leads to unusually high domestic migration between Louisiana and other states.
3. *Net international migration:* we use the national projected net international migration 2012-2060 (United States Census Bureau 2012 National Population Projections.), and then using the similar method as in the step 2 to adjust the county international migration rate for the period of 2000-2010.
4. In the final step, we take the 2016-2050 birth rate, death rate, net domestic migration rate, and net international migration calculated as above to generate the population growth rate.

Demand and supply

We construct a spatially explicit relative water stress index as:

$$Water\ Stress\ Index_{i,t} = \frac{1 + Population\ growth\ rate_{i,t}}{1 + Water\ supply\ change_{i,t}} \tag{3}$$

A positive population growth rate tends to increase water stress, and a negative water supply change also tends to increase water stress. For example, if the population in the year *t* is 20% more than the population in the baseline year, and the water supply in the year *t* is 10% less than the water supply in the baseline year, according Equation (3), our relative water stress index in the year *t* as compared to the baseline year will be (1 + 20%)/(1 - 10%) ≈ 1.33%.

Assumptions

In this study, we have made the following major assumptions:

1. We assume that climate change will not change per capita water demand, while higher temperatures and lower precipitations are likely to increase agricultural water use. Meanwhile, with higher temperature, people need more water. However, this increasing water use may or may not be offset by possible improving water use efficiency in other economic sectors, which are beyond the scope of this paper. For the purpose of simplicity, we assume a constant per capita water use to the year 2050.
2. While we project annual water stress, it should be noted that summer may have more water stress and winter may have less water stress as compared to the annual average. And this summer and winter difference may also vary spatially.
3. As we predict water stress for the period of 2016-2050, we implicitly assume that the policymakers do not improve water management, such as allocating water among different regions, which will change water stress. Thus, in this paper, we assume a world without adaptation.

RESULTS & DISCUSSION

Figure 2 shows the water supply changes for the years 2020, 2030, 2040, and 2050, downscaled to the U.S. county level from Milly et al. (2005)'s projections. It shows that future water supply will decrease more in the western U.S., while it will increase in the eastern U.S., following a trend that the wet gets wetter and the dry gets drier.

Figure 3 shows the relative water stress maps for the years 2020, 2030, 2040, and 2050, as compared to the baseline year 2016. It is observed that these water stress maps are different from water supply map in Figure 2 with higher spatial heterogeneity, indicating the importance of accounting for water demand when estimating the water stress. Some regions have mild water supply change, but if they have high population growth rates, they may still suffer from a worsening water stress. Meanwhile, if the water supply decrease is coupled with a shrinking population, the water stress may not increase in that region. Also, there are some regions with less water stress as compare to the year 2016, mostly located in the midwest, or locations with poor economic development, thus losing population.

However, based on Figure 3, it is not obvious whether the west or east has more severe water stress changes in general, as many metropolitan areas in the east also have worsening water stress in the coming decades. Therefore, in Figure 4, we plot the boxplots separately for the counties located in the east or west of the 100th meridian, a rough boundary between the eastern and western U.S. In Figure 4, it is observed that the western U.S. has higher relative water stress as compared to the baseline year, while the eastern U.S. generally has mild water stress changes. Furthermore, the regional difference in water stress changes become larger over the years, indicating a larger water stress difference across the space in the long run.

CONCLUSIONS

In this paper, we present the relative water stress maps for the contiguous U.S. counties for the years 2020, 2030, 2040, and 2050. Our projections are made by considering both water supply changes and water demand changes. It is observed that a water stress map is different from a water supply map, largely due to the fact that population growth rate are different in different part of the country. It should be noted that future population movement may be affected by water stress, e.g., people may tend to move away from regions with severe water stress. Thus our water stress maps do not show an actual water stress projection, instead, it illustrates the water stress changes assuming a fixed socio-economic condition. However, future population movement may be unaffected by water stress if the society to can find a way to relieve the water stress in the west or improve the water use efficiency.

In general, we find that the western U.S., already experiencing more drought than the eastern U.S., are expected to experience more severe water stress in the near future, and this pressure comes from both lower water supply and higher water demand. Meanwhile, although the water issue is less severe in the eastern U.S., many metropolitan areas, especially those with fast economic growth/population growth, e.g. Atlanta, are also going to face severe water stress despite a good water supply.

Our results should provide policymakers with useful information about the changes in the future water stress in the U.S. It indicates that water resource managers should focus on the regions with worsening water stress, such as exploring new water source, or improving water use efficiency.

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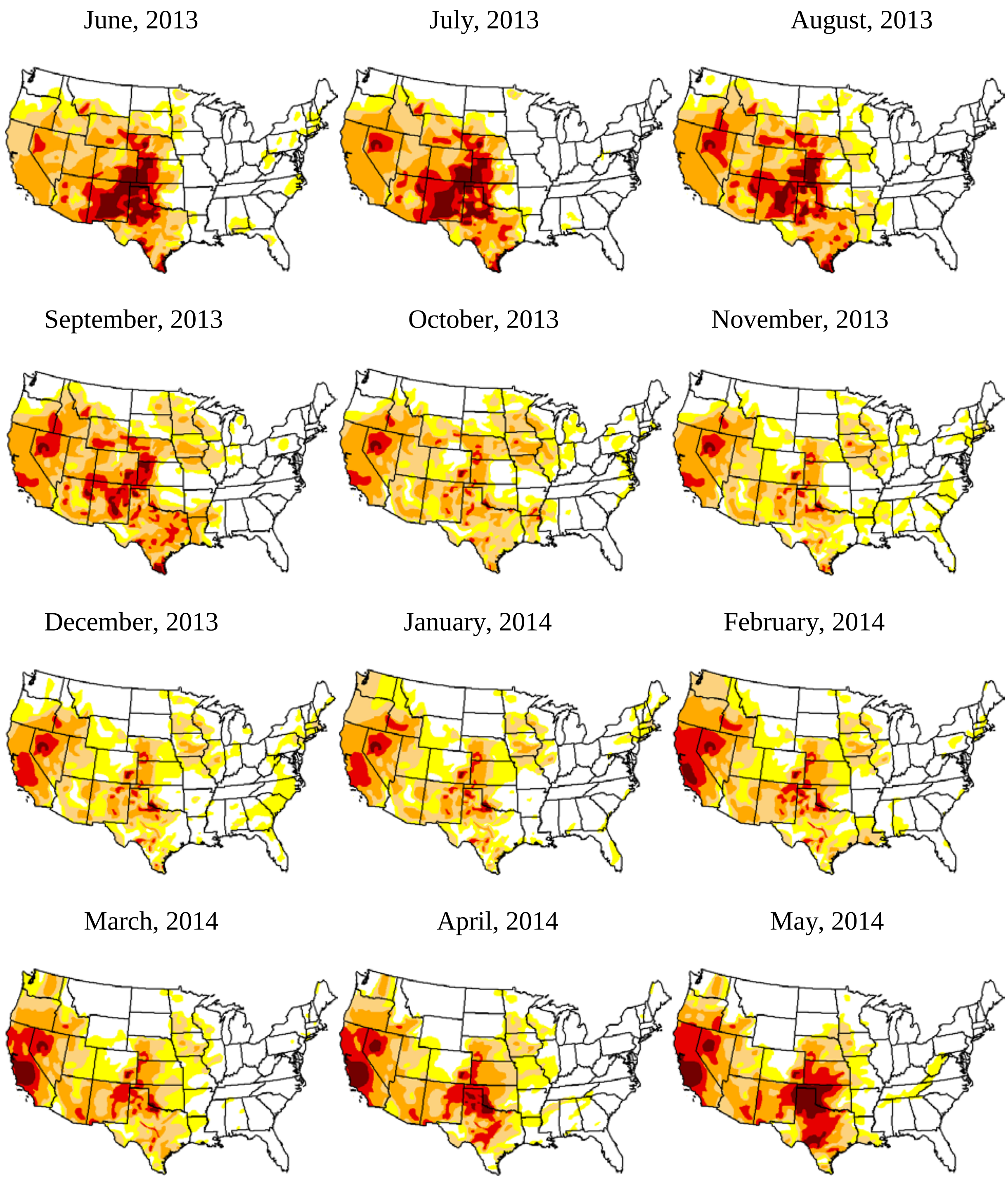

Figure 1. Contiguous U.S. Drought Monitor Map from June 2013 to May 2014. Red color means severe drought. Monthly observations in other years have the similar drought patterns. It is obtained from *http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx*

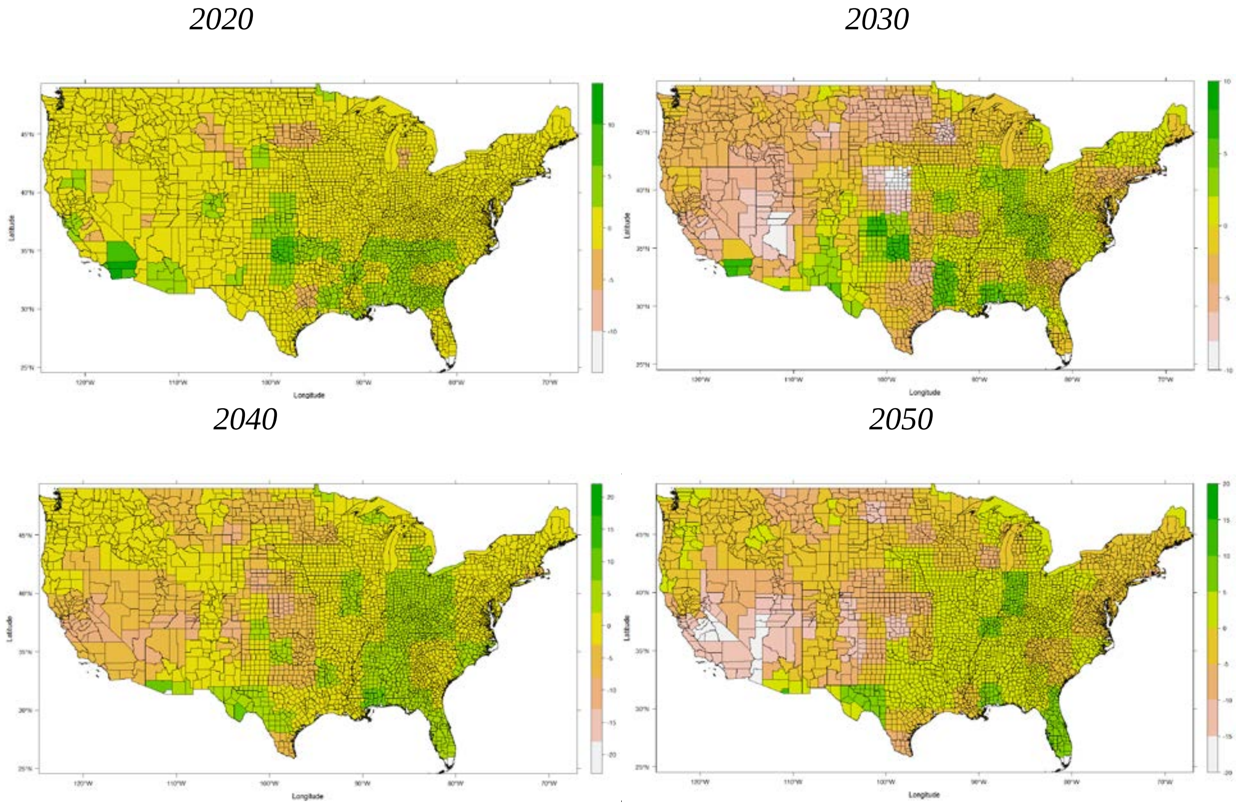

Figure 2. The spatial distribution of water supply changes. Water supply changes are based on the projections from Milly et al. (2005). The value in the maps are the percentage changes of water supply as compared to the 2016 value.

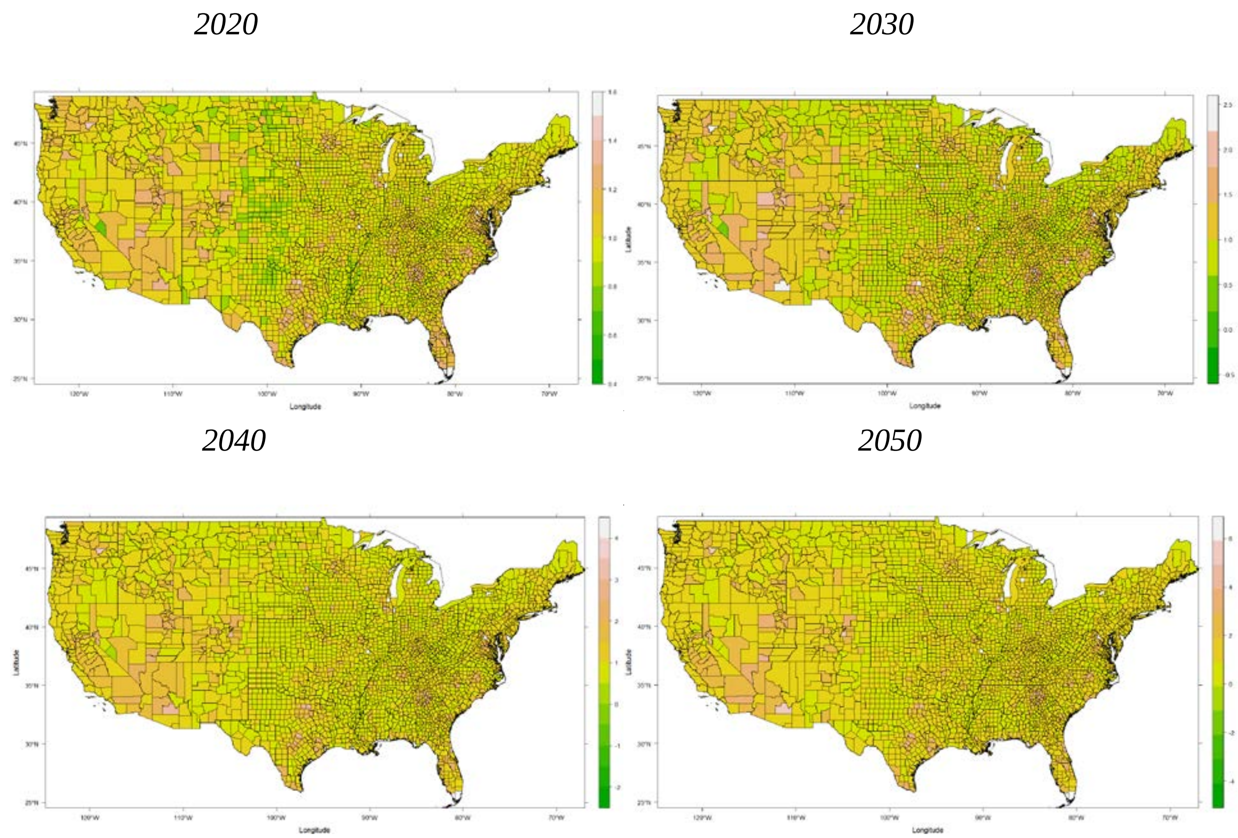

Figure 3. The spatial distribution of relative water stress index. Relative water stress indicates the ratio of water stress as compared to the baseline year 2016, which is assumed to have a water stress of 1.

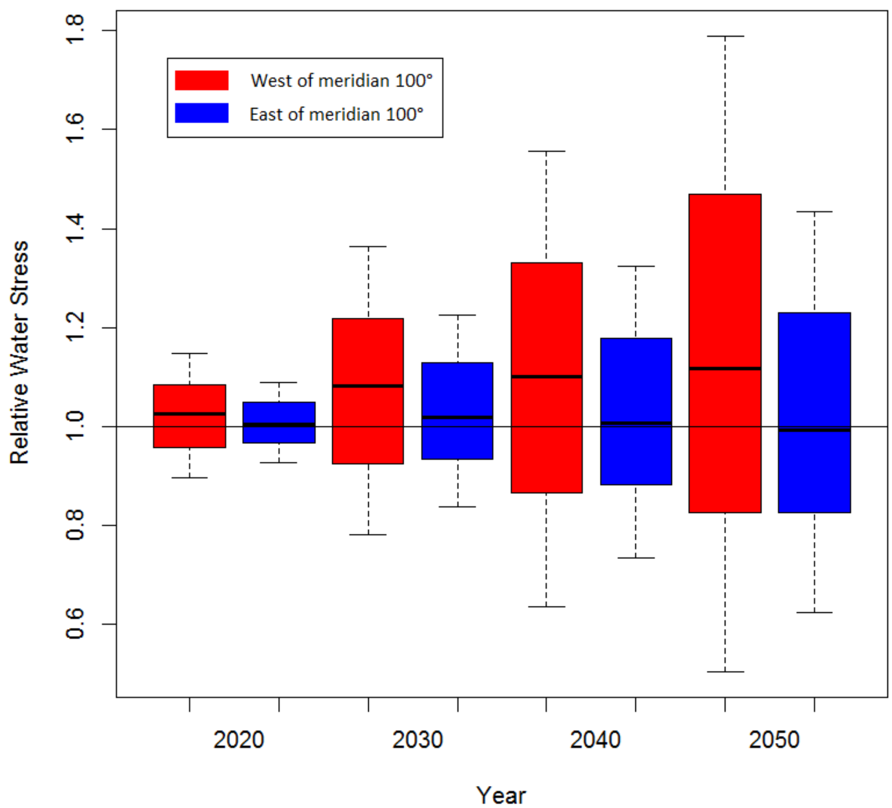

Figure 4. Boxplots of relative water stress for the counties located in the east and west of the 100th meridian. Relative water stress indicates the ratio of water stress as compared to the baseline year 2016, which has a relative water stress of 1.