ENVIRONMENTAL RESEARCH
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Environmental Research Communications

OPEN ACCESS

RECEIVED
26 January 2021

REVISED
23 April 2021

ACCEPTED FOR PUBLICATION
27 May 2021

PUBLISHED
7 June 2021

PAPER

Shifts in hydroclimatology of US megaregions in response to climate change

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Keywords: hydroclimatology, Megaregions, climate change, Budyko framework

Supplementary material for this article is available online

Abstract

Most of the population and economic growth in the United States occurs in megaregions as the clustered metropolitan areas, whereas climate change may amplify negative impacts on water and natural resources. This study assesses shifts in regional hydroclimatology of fourteen US megaregions in response to climate change over the 21st century. Hydroclimatic projections were simulated using the Variable Infiltration Capacity (VIC) model driven by three downscaled climate models from the Multivariate Adaptive Constructed Analogs (MACA) dataset to cover driest to wettest future conditions in the conterminous United States (CONUS). Shifts in the regional hydroclimatolgy and basin characteristics of US megaregions were represented as a combination of changes in the aridity and evaporative indices using the Budyko framework and Fu's equation. Changes in the climate types of US megaregions were estimated using the Fine Gaussian Support Vector Machine (SVM) method. The results indicate that Los Angeles, San Diego, and San Francisco are more likely to experience less arid conditions with some shifts from Continental to Temperate climate type while the hydroclimatology of Houston may become drier with some shifts from Temperate to Continental climate type. Additionally, water yield is likely to decrease in Seattle. Change in the hydroclimatology of Denver and Phoenix highly depends on the selected climate model. However, the basin characteristics of Phoenix have the highest sensitivity to climate change. Overall, the hydroclimatic conditions of Los Angeles, San Diego, Phoenix, Denver, and Houston have the highest sensitivity to climate change. Understanding of future shifts in hydroclimatology of megaregions can help decision-makers to attenuate negative consequences by implementing appropriate adaptation strategies, particularly in the water-scare megaregions.

1. Introduction

The conterminous United States (CONUS) can be divided into large contiguous geographical regions referred to as 'megaregions' centered on major cities (Nelson and Rae 2016). The megaregions represent clusters of cities across the CONUS in terms of economic structures, culture, history, topography, natural resources, ecosystem, climate, urban growth telecommunication, and institutions (Hagler 2009, Nelson and Rae 2016, Nelson 2017). Most of the US population and economic growth has been concentrated in megaregions (Ross 2008). Improving policies, planning, and investments at the megaregional scale can address new challenges arising around the large metropolitan centers that can affect environment, economy, and society (Ross 2008, Nelson 2017, Hemmati *et al* 2020).

Rapid population growth, expansion of suburban areas, social equity, strained ecosystems are key challenges that US megaregions are currently experiencing (Ross 2008). Climate change may further exacerbate existing problems in metropolitan and regional planning over the 21st century by negative impacts on energy sources, water supply, air quality, habitat preservation, ecosystem, and natural resources (Ashfaq *et al* 2013, Ponce Campos *et al* 2013, Greve *et al* 2014).

Current megaregions planning strategies mostly focused to deal with issues such as transportations and underestimate the need to deal with future changes in climate and freshwater availability of megaregions (Dewar and Epstein 2007). Improved characterization of future shifts in long-term hydroclimatology of US megaregions may help planners, researchers, and decision-makers to attenuate the potential consequences of climate change on cities and strengthen economic prosperity (McDonald *et al* 2011, Butler *et al* 2017, Brown *et al* 2019).

Most previous studies that discussed changes in future US hydroclimatology have mainly focused on a particular region or individual parameters such as streamflow, precipitation, and evaporation (Wang and Hejazi 2011, Renner *et al* 2012, Ashfaq *et al* 2013, Weiskel *et al* 2014, Naz *et al* 2016), lacking a comparative study on the impacts of climate change on the integrated shifts in regional hydroclimatology of US megaregions as the combination of changes in aridity and evaporative indices. The US megaregions can variously respond to climate change due to different climatic, ecological and physiographical properties (Abatzoglou and Ficklin 2017, Piemontese *et al* 2019).

This study examines the effects of climate change on the hydroclimatic conditions of fourteen US megaregions including Seattle, San Francisco, Los Angeles, San Diego, Denver, Phoenix, Chicago, Miami, Washington D.C., Philadelphia, New York, Boston, Houston, and Atlanta. Assessing changes in long-term anomalies such as shifts in hydroclimatology may provide insights to support future water resource planning and management. This issue is of particular importance because many megaregions may do not have sufficient natural resources to overcome hydroclimatic changes, particularly in water-scarce regions (Maliva and Missimer 2013).

We characterized possible changes in hydroclimatic conditions and basin characteristics of fourteen US megaregions from current (1986–2015) to future (2070–2099) periods under DRY, MIDDLE and WET climate conditions. Specifically, the objectives of this study are to: (1) investigate the effects of climate change on hydroclimatic conditions of US megaregions using the Budyko framework; (2) assess and compare shifts in basin characteristics using Fu's equation; (3) characterize shifts in climate types of US megaregions using the Fine Gaussian Support Vector Machine (SVM) method; and (4) determine the hotspots of megaregions which show consistent changing signals across all selected climate models. Improved understanding of future change in hydroclimatolgy of megaregions can play a major role in the future urban planning and water resource management under the sustainable growth.

2. Methods

In this section, the concept of US megaregions is first described. Fourteen megaregions were selected to assess the effects of climate change on hydroclimatolgy of US metropolitan areas with rapid population and economic growth. The Budyko framework was used as the combination of aridity and evaporative indices to characterize long-term shifts in hydroclimatic conditions of US megaregions. The Fu's equation was then applied to estimate changes in integrative basin characteristics of megaregions. Finally, the SVM method was used to identify megaregions that are likely to experience shifts in their climate type according to the Koppen climate classification.

2.1. US Megaregions

The US Megaregions are formed based on similar societal and geographical characteristics (Nelson and Rae 2016). Cities inside each megaregion have common natural resources, ecosystem, settlement, and land use pattern. Fourteen US megaregions were selected from Nelson and Rae (2016) to assess the effects of climate change on US megaregions (figure 1). These megaregions were selected due to their importance and various eco-hydrologic and climatic regimes which represents a wide spectrum of climate, demographic, policy, and cultural settings (Todorovich 2009). Boston, New York, Philadelphia, and Washington D.C. megaregions were merged as a large megaregion (WPHNB) given their geographical proximity. Similarly, Los Angeles and San Diego were combined to one LOS-SAN megaregion because of their similar hydroclimatic conditions.

The selected megaregions are located in various climate (Chen and Chen 2013), ecological (Omernik and Griffith 2014), physiographical, and landform (ESRI 2014) regions, which require a CONUS-wide hydroclimate modeling effort to support the analysis across varying geographical conditions. Figure S1 (available online at stacks.iop.org/ERC/3/065002/mmedia) illustrates the regional conditions of each megaregion.

Nelson (2017) reported the projected population, and economy of the US megaregions based on the Wood and Poole Economics (2016). Approximately, 76% of the US population is concentrated in the megaregions, whereas the US megaregions occupy only a small land area of the CONUS. Houston, Phoenix, and Miami

Figure 1. The Selected US Megaregions.

megaregions were projected to experience the highest increase in population. The economic growth was measured by changes in gross regional product (GRP). Miami, Houston, and phoenix were estimated to experience double GRP (Nelson 2017).

These regions encompass climate regimes from coastal moist mid-latitude climates of the Mid-Atlantic to the subtropical semi-arid deserts of the Southwest (Nelson and Rae 2016). However, climatic conditions of megaregions are estimated to change faster than the global mean climate over the 21st century (America 2050 2006, Nelson 2017).

2.2. Hydroclimate projections

We evaluated the current and future hydroclimate conditions in each megaregion through CONUS hydrologic simulation driven by observed and projected forcing datasets (Heidari *et al* 2020b). The observed 1986–2015 daily meteorologic forcing dataset at 1/24° (~4 km) grid resolution was organized by Naz *et al* (2016). Both precipitation and temperature were based on the Daymet (Thornton *et al* 1997) dataset and rescaled by the Parameter-elevation Regressions of Independent Slopes Model (PRISM, Daly *et al* 2008) dataset at the monthly scale. The wind speed was bilinearly interpolated from the 32 km resolution North American Regional Reanalysis (NARR) dataset (Mesinger *et al* 2006) to each of the 1/24° (~4 km) grid.

The 2070–2099 future climate were obtained from the downscaled Multivariate Adaptive Constructed Analogs (MACA, Abatzoglou and Brown 2012) dataset at the same 1/24° (~4 km) grids. Given the nature of global climate modeling, the projected changes in future climate conditions may widely differ across models and simulations. Overall, the projected changes of future precipitation are generally more uncertain than temperature.

Among the available MACA models, we selected three climate models ranging from wettest to driest under the highest RCP 8.5 emission scenario to capture the wide range of possible future climate changes (Heidari *et al* 2020b, 2021). The WET (CNRM-CM5), DRY (IPSL-CM5A-MR) and MIDDLE (NorESM1-M) climate models were selected based on a range of changes in precipitation from current to future conditions. While these three selected climate models only represent a small subset of a much larger number of models and emission scenarios, the use of DRY, MIDDLE, and WET climate models under RCP 8.5 allows us to capture the largest range in projected hydroclimatic conditions across the CONUS. Readers are referred to Heidari *et al* (2020b) and Joyce and Coulson (2020) for further details on model selection.

The Variable Infiltration Capacity (VIC) hydrological model (Liang *et al* 1994) was used to simulate the hydrologic responses to projected future climate conditions across the CONUS. The CONUS VIC model parameters used in this study were organized and calibrated by Oubeidillah *et al* (2014) and Naz *et al* (2016). In each of the 8-digit Hydrologic Unit (HUC8) basins across the CONUS, the monthly VIC total runoff (water yield) was calibrated by the US Geological Survey WaterWatch runoff dataset (Brakebill *et al* 2011). VIC outputs including the daily precipitation, evaporation, temperature, water yield (or streamflow), and potential evapotranspiration were aggregated to annual scales for each HUC8. The hydroclimatic parameters of US

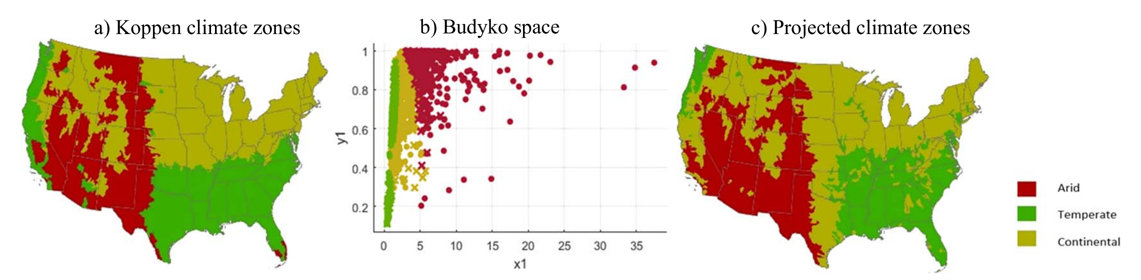

Figure 2. (a) US Koppen climate zones, (b) Clustering Budyko space based on Koppen climate classification, (C) Projected US Climate zones based on the Budyko space classification.

megaregions were then calculated according to the HUC8 basins where the megaregions are located. Figure S2 compares the 1986–2015 observed versus simulated mean annual water yield for HUC8 basins within the US megaregions. The VIC model shows a strong linear correlation (0.9707) between observed and simulated mean annual water yield. Readers are referred to Heidari *et al* (2020b) for further modeling details.

2.3. Budyko framework and Fu's equation

We applied the Budyko space and Fu's equation in this study to assess the impacts of climate change on hydroclimatic conditions and basin characteristics of US megaregions. Fu's one-parameter equation (equation (1)) can account for the joint influence of factors such as aridity index, evaporative index, basin size, seasonal variability, and soil and vegetation characteristics, and have been used by multiple studies (Zhang *et al* 2004). The Fu's equation is defined as:

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{\omega}\right]^{\frac{1}{\omega}} \tag{1}$$

where $\frac{ET}{P}$ is evaporative index, $\frac{PET}{P}$ is aridity index, and ω is a dimensionless parameter.

The aridity and evaporative indices were estimated using the projected hydroclimatic projections from section 2.2. In the Budyko space, movements toward the right indicate more arid climatic conditions while movements toward the left mean less arid climatic conditions. Movements downward is a sign of higher river discharge or wetter conditions while moving upward refers to the condition in which water yield or streamflow decreases (Jaramillo *et al* 2018).

The current and future ω can be calculated from equation (1). Change in ω is highly associated with changes in basin characteristics such as land cover, vegetation cover, type and productivity (Zhao *et al* 2009, Coe *et al* 2011, Zhang and Wei 2012, Zhou *et al* 2015). Change in the ω can evaluate how climate and hydrological changes interactively affect basin characteristics (Zhou *et al* 2015, Ning *et al* 2019). Some studies reported that ω can be influenced by soil properties such as water holding capacity (Porporato *et al* 2004, Donohue *et al* 2012, Abatzoglou and Ficklin 2017, Heidari *et al* 2020b).

Significant changes in the integrative basin properties of US megaregions may considerably affect future agricultural, economic, social, ecosystemic and environmental activities, especially in the megaregions with insufficient natural and water resources and rapid population and economic growth.

2.4. Changes in the regional climate zones

The Koppen climate classification has been widely used to divide the United States to main climate groups including Arid, Temperate, Continental, and Tropical based on the empirical relationship between climate and vegetation (Chen and Chen 2013). However, megaregions may shift from one type to another in the future. To understand this, we first determined the major regional climate zone of each HUC8 river basin (figure 2(a)). Then, the Fine Gaussian SVM (Cristianini and Shawe-Taylor 2000) was applied to divide the Budyko space into three regions based on the Koppen Climate Classification and current aridity and evaporative indices. Koppen Climate Classification-Level1 has a high accuracy (76.2%) to classify Budyko space to three Regions. Figure 2(b) provides classification of the Budyko space based on the Koppen climate classification. Figure 2(c) illustrates the classified climate zones using the Fine Gaussian SVM.

Arid region is pretty close to the water limited condition while the temperate region is close to the energy limited condition, and the Continental region is somewhere between the Arid and Temperate regions. In this study, spatial changes in climate types of the US megaregions were projected using shifts in the Budyko space. The economic and population growths of US megaregions can be highly influenced by climate change, especially in regions that are likely to experience new climate regime in the future. Rapid population and economic growth combined with considerable shifts in climate and water resources in the megaregions may beget irrecoverable consequences at national scale. Planners, policy makers and politicians may improve preparedness by providing an insight to future changes in advance and implementing adaptation and mitigation strategies.

3. Results and discussion

The hydroclimatology of US megaregions may respond differently to future climate change. While some regions such as Houston are more likely to experience long-term drying periods in the future, some regions such as Los Angeles, San Diego, and San Francisco are more likely to experience long-term wetting periods in the future. Besides, the megaregions like Phoenix may have significant changes in their integrative basin characteristics. The climate types of basins in Seattle and Houston have respectively the lowest and highest shifts in response to climate change. This section is aimed to provide an improved understanding of the effects of climate change on hydroclimatic conditions and basin characteristics of fourteen US megaregions.

3.1. Hydroclimatic conditions

The historic hydroclimatic conditions including the 30-year average of precipitation, evaporation, water yield, evapotranspiration, and temperature of the fourteen US megaregions are shown in figure S3. Overall, Seattle has the highest amount of precipitation and water yield. Los Angeles, San Diego (LOS-SAN), Phoenix, and Denver have the lowest amount of historic precipitation, water yield, and evaporation. Miami, Houston, and Atlanta have the highest amount of evaporation and temperature. The variation in 30-year potential evapotranspiration of US megaregions is comparatively small compared to other hydroclimatic variables. Seattle has the lowest amount of potential evapotranspiration among all US megaregions.

Changes in hydroclimatic conditions of US megaregions from current (1986–2015) to future (2070–2099) periods are provided in figure S4 using DRY, MIDDLE, and WET climate models. Los Angeles, San Diego (LOS-SAN), San Francisco, and Phoenix have respectively the highest changes in precipitation. The precipitation and water yield in Los Angeles, San Diego (LOS-SAN), San Francisco, Washington D.C, Philadelphia, New York, Boston (WPHNB), and Seattle are more likely to consistently increase under all three climate models. Houston is more likely to experience a consistent decrease in precipitation and water yield under the three climate models. However, change in 30-year average precipitation and water yield of Phoenix, Denver, Miami, and Atlanta highly depends on the future climate model.

The potential evapotranspiration in Houston, Washington D.C, Philadelphia, New York, Boston (WPHNB), and Seattle is more likely to increase from current to future conditions. Although San Francisco is more likely to experience small changes in potential evapotranspiration, Phoenix, Denver, Miami, Atlanta, Los Angeles, San Diego, and Chicago shows various responses in potential evapotranspiration based on the future different climate model.

3.2. Changes in hydroclimatic conditions

The current aridity and evaporative indices of US megaregions are illustrated in figure S5. Los Angeles, San Diego (LOS-SAN), Phoenix, Denver, and San Francisco have a high aridity index indicating that these regions are more limited by water availability. Additionally, these regions have a high evaporative index meaning that a considerable amount of precipitation is likely to evaporate from these regions.

Other US megaregions including Chicago, Miami, Houston, Atlanta, Washington D.C, Philadelphia, New York, Boston (WPHNB), and Seattle have around the same aridity index under the current climate conditions. However, Chicago, Miami, Houston, and Atlanta have a higher evaporative index compared to Washington D.C, Philadelphia, New York, Boston (WPHNB), and Seattle. The finding indicates that while these regions have the same ratio of potential evapotranspiration to precipitation under current conditions, water yield (or streamflow) is lower in Washington D.C, Philadelphia, New York, Boston (WPHNB), and Seattle.

Figure 3 shows changes in aridity and evaporative indices of US megaregions in response to future climate change. Although variability in the projection of future hydroclimatic shifts is dominated by variability in climate change scenarios, projected changes in future hydroclimatology of US megaregions showed some consistency across climate change models in terms of the direction and magnitude of changes.

Changes of aridity index are projected to be small in Seattle, Chicago, Miami, Washington D.C, Philadelphia, New York, Boston (WPHNB), and Atlanta, indicating that climate change may have relatively small impacts on regional climatology in these regions. However, the aridity index of Los Angeles, San Diego, and San Francisco are projected to decrease consistently across DRY, WET, and MIDDLE climate models. This finding indicates that these regions are more likely to experience less arid climate conditions in the future.

The aridity index of Denver and Phoenix is highly dependent on climate models. While the aridity index may increase under the DRY climate model, it may remain constant under the MIDDLE climate model and decrease

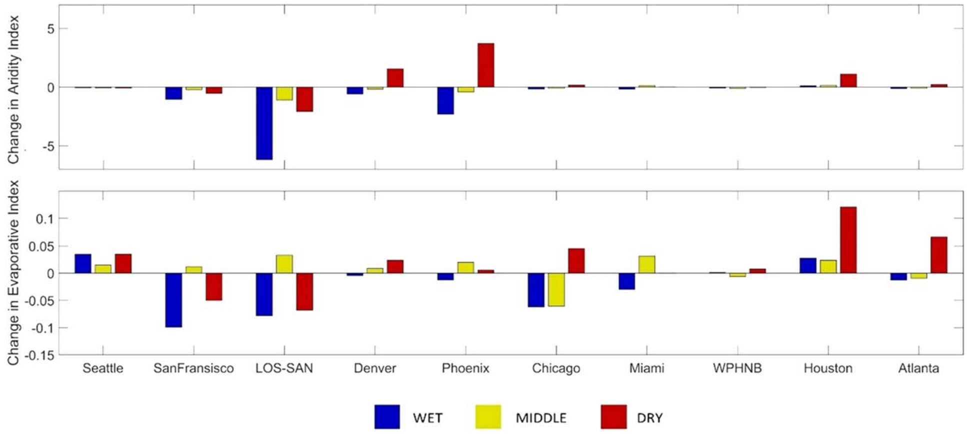

Figure 3. Change in 30-year average of hydroclimatic indices of the US megaregions from current to future conditions.

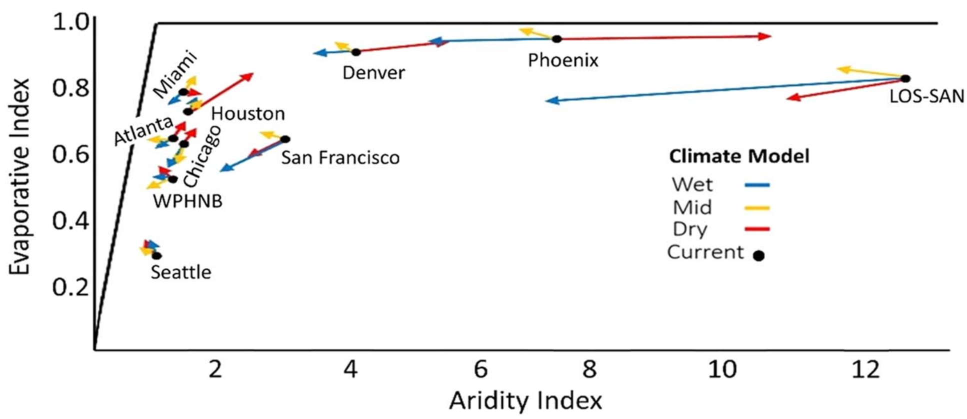

Figure 4. The average movements of US Megaregions from current to future climate conditions.

under the WET climate model. However, Houston is the only megaregion that consistently have an increasing aridity index under the three climate models, indicating that Houston is more likely to have more arid climatic conditions by the end of the century.

Houston and Seattle are the only megaregions that show consistently increasing evaporative index, indicating that river discharge is more likely to decrease in these regions in the future. The evaporative index of other regions highly depends on the future climate model. While Denver, Washington D.C, Philadelphia, New York, Boston (WPHNB), and Phoenix show the lowest change in evaporative index in response to climate change under all three climate models, the evaporative index of San Francisco, Los Angeles, San Diego, Chicago, Atlanta, and Miami is highly variable in the future according to the selected climate model.

Figure 4 shows the movement of each megaregion in the Budyko space under the DRY, MIDDLE, and WET climate models as the representation of changes in hydroclimatic conditions of each region. Houston is moving to the upper-right quadrant of the Budyko space under the three climate models meaning that Houston is more likely to get warmer and drier in the future. San Francisco, Los Angeles, San Diego (LOS-SAN), Washington D.C, Philadelphia, New York, Boston (WPHNB) are moving to the left quadrant of the Budyko space under the three climate models indicating that these regions are more likely to experience less arid climatic conditions in the future. Seattle is moving to the upper-left quadrant of the Budyko space under the three climate models meaning that the evaporative index is increasing while the aridity index is decreasing.

3.3. Changes in basin characteristics

In this section, we used the Fu's equation to characterize the effect of hydroclimatic change on basin characteristics of US megaregion using the DRY, MIDDLE, and WET climate model. The basin characteristics of megaregions with a higher percentage of changes in ω are more sensitive to future estimated hydroclimatic change. Table 1 provides current and future ω under the DRY, MIDDLE, and WET climate model for the

Table 1. Current and future ω of US megaregion.

Mega region	Current	WET	MIDDLE	DRY
Seattle	1.31	1.38 (+5%)	1.35 (3%)	1.39 (6%)
San Francisco	1.53	1.50 (−2%)	1.57 (3%)	1.50 (−2%)
LOS-SAN	1.53	1.52 (−1%)	1.62 (6%)	1.45 (−5%)
Denver	2.18	2.25 (3%)	2.27 (4%)	2.16 (−1%)
Phoenix	2.15	2.25 (5%)	2.40 (12%)	2.03 (−6%)
Chicago	1.82	1.74 (−4%)	1.71 (−6%)	1.88 (3%)
Miami	2.46	2.49 (1%)	2.52 (2%)	2.44 (−1%)
WPHNB	1.69	1.74 (3%)	1.74 (3%)	1.73 (2%)
Houston	2.14	2.19 (2%)	2.14 (0%)	2.17 (1%)
Atlanta	1.98	2.06 (4%)	2.04(3%)	2.07 (5%)

fourteen US megaregions. Changes in ω can be a sign for shifts in physiography, ecology, land cover, vegetation cover, and basin slope (Zhao *et al* 2009, Coe *et al* 2011, Zhang and Wei 2012).

Phoenix has the highest change in ω under all climate models, indicating that the basin characteristics of Phoenix such as physiography and ecology are more likely to experience significant shifts in response to the future hydroclimatic changes. Houston, San Francisco, Miami, Washington D.C, Philadelphia, New York, Boston (WPHNB) has comparatively lower changes in ω meaning that the basin characteristics of these regions are less sensitive to future hydroclimatic changes.

In this study, we only focused on applying Fu's equation to characterize the US megaregions that have the highest change in their basin characteristics in response to future hydroclimatic changes. Finding a statistical correlation between ω and various basin characteristics such as slope, physiography, ecology, landcover is more complicated and beyond the scope of this study.

3.4. Spatial changes in the climate types of US Megaregions

Changes in the spatial extent of climate types were also characterized by changes in the areas occupied by the Koppen climate types (figure 5). Under the WET and MIDDLE scenarios few HUC8 basins show change in climate classification. Under all three climate scenarios, some basins in the Washington D.C, Philadelphia, New York, and Boston (WPHNB) are projected to change from Continental to Temperate climate type. Under the WET scenario, some basins in Denver, Los Angeles, San Diego, Phoenix, and San Francisco megaregions are likely to change from Arid to Continental climate type. However, under the MIDDLE scenario, some basins in Los Angeles, San Diego, Phoenix, and Denver may experience shift from Continental to Arid.

Under the DRY climate scenario, most basins in Houston are likely to experience shifts in their climate type from Continental to Arid, or from Temperate to Continental. Additionally, most basins in Atlanta are projected to change from Temperate to Continental. Some basins in Denver megaregion are likely to change from Continental to Arid climate type.

3.5. Uncertainty and model limitations

Although the results of this study provide some possible insights about the potential effects of future climate change on hydroclimatic conditions of the US megaregions, a variety of other factors such as climate model and emission scenario selection, downscaling, and hydrological simulation can affect the outcomes of the analysis. Additionally, reservoir regulation and interbasin water transferred to support each megaregion was also not specifically addressed. Therefore, while the finding of this study provides an improved understanding of the future hydroclimatology and basin characteristics of US megaregions, it is not an exact prediction of future conditions.

Our findings are sensitive to the choice of downscaled climate models. The selected MACA climate models can be uncertain due to their dependency on future emission scenarios and downscaling approach. The results presented in this study under DRY, MIDDLE and WET climate models are indicative of the effect and the uncertainty associated with future climate change impacts on the hydroclimatology of US megaregions. Note that WET, and DRY indicate the MACA climate models that are on average the wettest, and driest models at the conterminous scale, respectively. Therefore, the DRY and WET climate models may not be always the driest and wettest models in all megaregions across the United States.

Furthermore, the internal climate variability and imprecise climate models can add higher level of uncertainties to future climate projections (Wyard *et al* 2020). On average, however, the results highlight that climate change would likely result in a substantial change in the hydroclimatic conditions of some regions such as Houston.

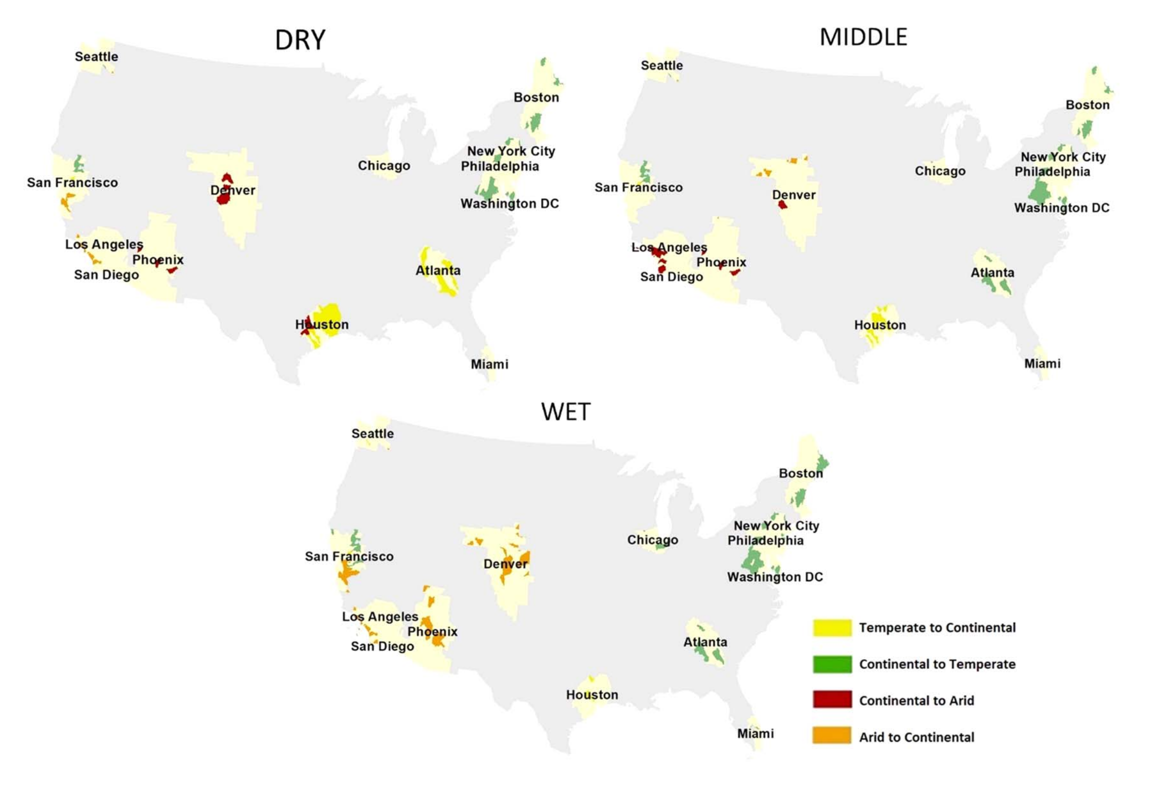

Figure 5. Shift in the US climate zones under three climate change scenarios.

In addition to the uncertainties of climate models, there are also uncertainties associated with VIC hydrological model such as model parameters and structural deficiencies (Melsen *et al* 2016, Gharari *et al* 2019, 2020). The VIC model may not fully capture all physical properties, changes in landcover and water management regulations (Naz *et al* 2016). The structural deficiencies and related assumptions of the VIC model was addressed in this study by aggregating outputs over longer time periods such as 30-yr averages (Gharari *et al* 2019). In addition, estimating changes in basin characteristics using ω can add other uncertainties which originate from the assumptions of Fu's equation.

The hydroclimatology of US megaregions can be also influenced by other anthropogenic factors such as rapid population growth. In the absence of any adaptive urban adaptation strategies, such as green, cool roof, and hybrid approaches, the temperature is expected to raise in response to the greenhouse gas-induced forcing (Georgescu *et al* 2014, Benson-Lira *et al* 2016). Increasing temperature itself can lead to shifts in hydroclimatic conditions of US megaregions.

In addition, in this study we only focused on watersheds overlapped with the selected megaregions. Water supply to some megaregions can be from watersheds/reservoirs outside of the regions or from groundwater resources that cannot be simulated by VIC. Besides, the aridity and evaporative indices applied in this study were only to represent shifts in long-term hydroclimatology of US megaregions. Characterization of future drought or flood events in these areas are complicated (Ghanbari *et al* 2019, 2020, Heidari *et al* 2020a) and can be a prospect for this study to assess vulnerability of US water supply systems to future drought and water shortage. We also did not evaluate socioeconomic consequences in these megaregions which are outside of the scope of the current research.

4. Summary and conclusions

Future planning at the megaregional scale provides an insight to emerging challenges (Nelson 2017). This study evaluates changes in hydroclimatology and basin characteristics of fourteen US megaregions in response to climate change using the Budyko framework. The findings indicate that the hydroclimatic responses of US megaregions may vary under WET, DRY, and MIDDLE climate models. There are some clear consistencies in regional shifts in long-term hydroclimatology and basin characteristics. The findings point out that Los Angeles, San Diego, and San Francisco may experience a decrease in aridity under all three climate models indicating that these regions may become less arid by the end of the 21st century. Additionally, Houston may experience more arid climatic conditions in the future by increasing aridity index under all three climate models.

Besides, the evaporative indices of Houston and Seattle are projected to increase by the end of the century under all three climate models indicating that the evaporative loss of freshwater resources in Houston and Seattle are likely to increase in the future. The population of Houston and Seattle megaregions is projected to increase significantly over the 21st century (Ross 2008, Nelson 2017). Thus, these metropolitan regions are likely to face more severe challenges in water resource planning and management in the future.

Phoenix is also the megaregion with the highest change in ω consistently across all three climate models, suggesting that the basin characteristics of Phoenix may experience significant changes in the future. Under all three climate models, basins in Houston are likely to experience shifts in their climate type from Temperate to Continental. Besides, some basins in Washington D.C, Philadelphia, New York, Boston (WPHNB) are projected to change from Continental to Temperate climate type.

These findings highlight the need for developing a national development strategy that addresses climate change policies to improve robust economic growth and protect vulnerable natural, water, and food resources in the US megaregions and hence reduce negative consequences on the economy, society, and environment. Hydroclimatic change accompanied with rapid population growth, urbanization and land use change in US megaregions can accelerate future challenges in the megaregions, particularly, water-scarce regions that may do not have the water and natural resources to overcome significant shifts in their hydroclimatology. This study can help decision-makers, planners, policy makers and politicians to improve the understanding, planning, and preparedness for the future hydroclimatic changes through the sustainable growth to protect natural areas and increase residential density.

Acknowledgments

This work was funded by NSF Sustainability Research Network (SRN) Cooperative Agreement 1444758 as part of the Urban Water Innovation Network (UWIN) and a cooperative agreement with US Forest Service Research and Development, Rocky Mountain Research Station. The baseline forcing data from 1980 to 2015 are provided by Naz *et al* (2016). The projected MACA climate data from 1950 to 2099 are provided by Abatzoglou and Brown (2012). The historic monthly runoff is obtained from the USGS WaterWatch runoff dataset (Brakebill *et al* 2011).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

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