Global and Planetary Change 143 (2016) 100–117

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Regional hydrologic response to climate change in the conterminous United States using high-resolution hydroclimate simulations☆

Bibi S. Naz [a,b], Shih-Chieh Kao [a,b,*], Moetasim Ashfaq [a,c], Deeksha Rastogi [a,c], Rui Mei [a,c], Laura C. Bowling [d]

[a] Climate Change Science Institute, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA
[b] Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA
[c] Computer Science and Mathematics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA
[d] Department of Agronomy, Purdue University, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 7 February 2016
Received in revised form 17 May 2016
Accepted 5 June 2016
Available online 16 June 2016

Keywords:
Hydroclimate change
Extreme events
CMIP5
RegCM4
VIC

ABSTRACT

Despite the fact that Global Climate Model (GCM) outputs have been used to project hydrologic impacts of climate change using off-line hydrologic models for two decades, many of these efforts have been disjointed — applications or at least calibrations have been focused on individual river basins and using a few of the available GCMs. This study improves upon earlier attempts by systematically projecting hydrologic impacts for the entire conterminous United States (US), using outputs from ten GCMs from the latest Coupled Model Intercomparison Project phase 5 (CMIP5) archive, with seamless hydrologic model calibration and validation techniques to produce a spatially and temporally consistent set of current hydrologic projections. The Variable Infiltration Capacity (VIC) model was forced with ten-member ensemble projections of precipitation and air temperature that were dynamically downscaled using a regional climate model (RegCM4) and bias-corrected to 1/24° (~4 km) grid resolution for the baseline (1966–2005) and future (2011–2050) periods under the Representative Concentration Pathway 8.5. Based on regional analysis, the VIC model projections indicate an increase in winter and spring total runoff due to increases in winter precipitation of up to 20% in most regions of the US. However, decreases in snow water equivalent (SWE) and snow-covered days will lead to significant decreases in summer runoff with more pronounced shifts in the time of occurrence of annual peak runoff projected over the eastern and western US. In contrast, the central US will experience year-round increases in total runoff, mostly associated with increases in both extreme high and low runoff. The projected hydrological changes described in this study have implications for various aspects of future water resource management, including water supply, flood and drought preparation, and reservoir operation.

1. Introduction

In the conterminous United States (CONUS), several studies based on modeling and observations show that climate change is resulting in the intensification of extreme precipitation and temperature (Diffenbaugh and Ashfaq, 2010), earlier snowmelt (Ashfaq et al., 2013; Abatzoglou, 2011; Mote, 2006), increases in the frequency and intensity of floods and droughts (Mahoney et al., 2012; Strzepek et al., 2010; Narisma et al., 2007; Frumhoff et al., 2007; Knox, 1993), and changes in the timing and magnitude of streamflow (Stewart et al., 2005; Milly et al., 2005). Such changes in hydrological conditions will have an immediate impact on local and regional communities and could have severe consequences for agriculture, property and human losses, energy production, and ecosystems. However, climate change impacts vary from region to region because of differences in geographical characteristics and local climate; thus hydrological response to climate change will be region-specific, depending on the dominant physical processes of a particular region (Hay et al., 2011). Therefore, it is necessary to understand the effects of projected climate change on regional hydrological cycles to support policy makers for more informed adoption and mitigation decisions. Additionally, understanding the spatial distribution of temporal variations of runoff is also important for water resource managers, because finer-scale modeling results can be used to infer practical water resource management decisions such as water allocation and reservoir operation.

☆ This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the US Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

* Corresponding author at: P.O. Box 2008, MS-6038, Oak Ridge, TN 37831-6038, USA.
E-mail address: kaos@ornl.gov (S.-C. Kao).

http://dx.doi.org/10.1016/j.gloplacha.2016.06.003
0921-8181/

Although a number of previous studies have investigated the impacts of climate change on water availability in the US, many of the studies focused on the western US (e.g., Rasmussen et al., 2014; Tohver et al., 2014; Hamlet et al., 2013; Ficklin et al., 2013; Barnett et al., 2004; Christensen et al., 2004; Payne et al., 2004; Stewart et al., 2005; Hamlet and Lettenmaier, 1999; Lettenmaier et al., 1999; Nash and Gleick, 1991; Milly et al., 2005; Seager et al., 2007; Seager and Vecchi, 2010; Mote et al., 2003). Comparatively few studies evaluated the future climate change impacts on the CONUS hydrology (e.g., Wolock and McCabe, 1999; Rosenberg et al., 2003; Thomson et al., 2005; Hay et al., 2011; Hagemann et al., 2013). Many of these past studies relied on hydrological outputs from Global Climate Models (GCMs) to drive one-way coupled hydrologic simulations. However, because of the coarser resolution of GCM grid cells, typically on the order of 150–200 km, hydrologic projections based on raw GCM outputs cannot be used directly for regional-scale water resource management studies. Thus, downscaling and bias-correction procedures are required to bring global climate change signals into watershed-scale hydrologic projections to support resource evaluation.

Different downscaling methods, such as bias-correction spatial disaggregation (BCSD; Wood et al., 2004), bias-correction constructed analogs (BCCA; Maurer et al., 2010), multivariate adaptive constructed analogs (MACA; Abatzoglou and Brown, 2012), and dynamical downscaling (e.g., North American Regional Climate Change Assessment Program; Mearns et al., 2012, 2013) have been used to support hydroclimate impact assessment in the CONUS (Hamlet et al., 2013; Christensen et al., 2004; Johnson et al., 2012; Glotter et al., 2014; Qiao et al., 2014; Takle et al., 2010; Elguindi and Grundstein, 2013; Bürger et al., 2011). In general, these methods either relied on statistical techniques that can be used to downscale temperature and precipitation from a large number of GCMs, or used computationally intensive regional climate models (RCMs) to downscale all hydroclimate variables in sub-daily time steps through physical relationships. Nevertheless, it should be noted that the effects of different downscaling methods on future hydroclimate projections have not been fully understood, and a consensus on the most suitable downscaling approach for future hydroclimate studies has yet to be reached (e.g., Chen et al., 2013).

In addition to the need for downscaling, the importance of fine-scale land surface modeling – particularly in topographically complex river basins, where topographic effects on hydrologic predictions are significant – has also been highlighted in a number of recent studies (Haddeland et al., 2002; Wood et al., 2011; Vano et al., 2014; Rasmussen et al., 2014). However, although these studies provide valuable watershed-scale hydroclimate information, the finer-resolution models have seldom been applied in a large study domain (e.g., regions or continents) mainly because of the data and computational limitations. In addition, given the differences in spatial and temporal resolution, model structure, and calibration approaches, the results from different finer-resolution studies cannot be inter-compared to provide a regionally coherent picture of future hydrology at a larger scale. To identify regions that are more sensitive to projected future climate changes (in terms of watershed-scale hydrologic response), a spatially and temporally consistent hydroclimate simulation framework is required.

To capture the fine-scale processes and to better understand regional and local hydrological responses to near future climate change, this study uses a hierarchal modeling framework to generate a large ensemble of computationally intensive hydroclimate projections for the evaluation of climate change impacts on regional hydrology across the entire CONUS. A hybrid dynamical and statistical downscaling is used for the refinement of GCM climate change signals for hydrologic simulation. While recent studies have demonstrated the added value of RCMs for impact assessment (Di Luca et al., 2012, 2013; Zhang et al., 2011; Chen et al., 2013; Elguindi and Grundstein, 2013), this study provides the most detailed (to date) characteristics of near-term regional and local hydroclimate projections using a high-resolution hydrologic model driven by ten dynamically downscaled and bias-corrected projections from an RCM. Here, we focus on understanding spatial and temporal hydrological change at the sub-basin scale in response to near-term future climate projections in the US. Changes in projected hydroclimate variables are further used to improve the understanding of the likely causes of changes in hydrological extremes, timing of peak runoff, and snow variables. Region-to-region variations in hydrological projection uncertainties are also examined. We present general methodology in Section 2, results in Section 3, discussion in Section 4, and conclusions in Section 5.

2. Methodology

2.1. Climate projections and downscaling

Using a hybrid downscaling approach (i.e., dynamical and statistical), coarser-resolution GCM outputs are first dynamically downscaled to 18 km resolution using the International Centre for Theoretical Physics Regional Climate Model version 4 (RegCM4) (Giorgi et al., 2012). Choice of RegCM4 is based on the extensive use of its earlier versions over the U.S. for high-resolution multi-decadal climate change simulations (e.g., Diffenbaugh et al., 2005, 2011; Mearns et al., 2012; Ashfaq et al., 2010; Mankin and Diffenbaugh, 2014). In total, ten Coupled Model Intercomparison Project phase 5 (CMIP5) GCMs under the Representative Concentration Pathway (RCP) 8.5 emission scenario (Table 1) are selected for downscaling. For each selected GCM, RegCM4 is forced at its lateral and lower boundaries every 6 h using atmospheric and sea-surface temperature fields from the GCM. The RegCM4 simulations are carried out at 18 km horizontal grid spacing with 18 vertical levels that cover a domain similar to that in Diffenbaugh et al. (2011). Each set of experiments consists of 41 years in the baseline (1965–2005) and 41 years in the near future (2010–2050) periods with the first year discarded for model spin-up.

The selection of GCMs is mainly based on data availability. Although more than 50 GCMs contributed to CMIP5, fewer than one-third archived three-dimensional atmospheric fields at a sub-daily timescale, which is necessary for dynamic downscaling. After balancing the resource limitations and the need for multimodel ensemble simulations (to better represent uncertainty across different GCMs), ten ensemble members, one from each different CMIP5 GCM, were selected. In addition, RCP 8.5 was selected, given that it is closest to the current observed trajectory. However, the performance and skills of each selected GCM are not specifically evaluated in this study.

In the second step of hybrid downscaling, the 18 km daily precipitation and maximum/minimum surface temperature from the RegCM4 simulation (both baseline and near future periods) are statistically bias-corrected to 1/24° (~4 km) resolution following the quantile-based bias correction approach, described in Ashfaq et al. (2010, 2013). The 1/24° (~4 km) resolution 1966–2005 monthly precipitation and temperature from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 2008) are used as the historic observations to support bias correction. Given that some of the Pacific Northwest watersheds are located in Canada and are not covered by PRISM, the 1/16° (~6 km) resolution gridded observations from Hamlet et al. (2013) are spatially interpolated to 1/24° (~4 km) resolution over that region. Similarly, for watersheds in Mexico that flow into the Rio Grande River basin, the 1/8° (~12 km) resolution precipitation and temperature from Maurer et al. (2002) are spatially interpolated to a consistent 1/24° (~4 km) domain to support bias correction in this region.

For statistical bias-correction, the 18 km RegCM4 fields are first spatially interpolated using bilinear interpolation to the targeted 1/24° (~4 km) geographical grid. The average monthly values are then calculated for both baseline and future periods and used to compute quantiles (40 intervals) for each calendar month in each grid. Between the 1966–2005 observation and baseline simulations, a model bias