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A climate change projection for summer hydrologic conditions in a semiarid watershed of central Arizona

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ABSTRACT

Potential climate change impacts on summer precipitation and subsequent hydrologic responses in the southwestern U.S. are poorly constrained at present due to a lack of studies accounting for high resolution processes. In this investigation, we apply a distributed hydrologic model to the Beaver Creek watershed of central Arizona to explore its utility for climate change assessments. Manual model calibration and model validation were performed using radar-based precipitation data during three summers and compared to two alternative meteorological products to illustrate the sensitivity of the streamflow response. Using the calibrated and validated model, we investigated the watershed response during historical (1990–2000) and future (2031–2040) summer projections derived from a single realization of a mesoscale model forced with boundary conditions from a general circulation model under a high emissions scenario. Results indicate spatially-averaged changes across the two projections: an increase in air temperature of 1.2 °C, a 2.4-fold increase in precipitation amount and a 3-fold increase in variability, and a 3.1-fold increase in streamflow amount and a 5.1-fold increase in variability. Nevertheless, relatively minor changes were obtained in spatially-averaged evapotranspiration. To explain this, we used the simulated hydroclimatological mechanisms to identify that higher precipitation limits radiation through cloud cover leading to lower evapotranspiration in regions with orographic effects. This challenges conventional wisdom on evapotranspiration trends and suggest that a more nuanced approach is needed to communicate hydrologic vulnerability to stakeholders and decision-makers in this semiarid region.

1. Introduction

The vulnerability of the southwestern U.S. to climate change is of particular interest to water managers as this arid and semiarid region has historically been characterized by high hydroclimatic variability (Sheppard et al., 2002; Woodhouse et al., 2010). Dramatic changes to seasonal snowpack amounts or timing might lead to a decreased reliability in water supply as well as a reexamination of water infrastructure operations. For example, Christensen et al. (2004) found that impacts from climate change projections would degrade the performance of water supply and hydropower systems in the Colorado River. Similarly, Serrat-Capdevila et al. (2013) found that a range of projected impacts from climate change in the Verde River will influence downstream water supply in Phoenix, Arizona for the bimodal precipitation of the region. While prior studies have focused on the winter season (e.g., Christensen et al., 2004; Seager et al., 2007), relatively little is known regarding the regional vulnerability to changes in the summertime North American monsoon (NAM). Cook and Seager (2013) indicate the possibility of a delay in NAM timing (typically from July to September), while Serrat-Capdevila et al. (2013), Bukovsky et al. (2013) and Robles-Morua et al. (2015) found increases in NAM precipitation from a range of different climate

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projections. The implications of a change in the NAM are of regional interest, in particular for downstream water managers who might need to adapt operations and infrastructure to handle variations in the bimodal precipitation regime.

The NAM in the southwest U.S. is characterized by convective storms that are localized in nature and of short duration and high intensity, leading to flooding in small areas over short time periods (Adams and Comrie, 1997; Gochis et al., 2006). As such, the use of coarse (monthly, 100 km resolution) general circulation models (GCMs) to provide inputs for regional watershed hydrology models has been criticized (see Wilby, 2010; Kundzewicz and Stakhiv, 2010). One approach to address this is through dynamical downscaling of GCM scenarios using mesoscale atmospheric models that can translate coarse projections into higher resolution (hourly, 10 km) meteorological forcing. This can help improve the reliability of climate simulations in regions with fine-scale features such as rugged terrain, water bodies or land cover differences (Castro et al., 2007; Dominguez et al., 2012), leading to more realistic precipitation fields. Similarly, the use of coarse hydrologic models in climate change assessments limits their ability to resolve the fine-scale meteorological forcing and watershed properties that control hydrologic responses, in particular during the NAM (e.g., Ellis et al., 2008; Serrat-Capdevila et al., 2013; Robles-Morua et al., 2015). Distributed hydrologic models, on the other hand, have a wider appeal for climate change impact studies due to their ability to provide insight on the spatial and temporal details of the rainfall-runoff transformation (e.g., Xu and Singh, 2004; Kampf and Burges, 2007).

In this study, we conduct high resolution (~120 m, hourly) hydrologic projections for summer conditions in a semiarid watershed of central Arizona. Our approach is based on developing meteorological fields over historical (1990–2000) and future (2031–2040) periods by using boundary conditions from a single GCM, the Hadley Center Coupled Model version 3 (HadCM3), with a mesocale simulation using the Weather Research and Forecasting (WRF) model. The meteorological fields are then applied as forcing in a distributed hydrologic model, known as the Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator (tRIBS), for the Beaver Creek watershed, located upstream of Phoenix, Arizona. Manual model calibration and model validation were performed using radar-based precipitation data during three summer seasons. Two additional products based on a rain gauge network and a reanalysis dataset were evaluated during these summer periods to illustrate the impacts of precipitation variability on the simulated hydrologic response. Hydroclimatological conditions during the NAM are then evaluated for historical and future periods to determine the propagation of precipitation and temperature changes into streamflow, soil moisture and evapotranspiration. We performed analyses of basin-averaged conditions across the two periods and the spatial distribution of differences between summer averages obtained for the two periods in an effort to quantify how spatial patterns aggregate to the entire Beaver Creek watershed. In doing so, we identify and explain mechanistically how the climate change projection affects radiation and water availability that control evapotranspiration. Furthermore, this study provides a foundation upon which to build modeling activities that test a wider range of climate or land use change projections for supporting regional water managers in decision-making under uncertainty.

2. Materials and methods

2.1. Study watershed and its characteristics

The Beaver Creek watershed is a sub-watershed of the Verde River (Fig. 1). With an area of approximately 1100 km^2, the watershed has variable terrain and landscape characteristics that are representative of the Mogollon Rim transition zone of central Arizona. Elevations range from ~1000 to 2600 m above sea level and are characterized by significant canyons incised into the Colorado Plateau. Land cover varies with elevation from desert shrub in the lowlands, through pinyon-juniper woodlands, and up to ponderosa pine forests at the higher elevations (e.g., Baker, 1999; Lopes et al., 2001). Soils are composed primarily of clay, clay loam and loam, developed on basalts and cinders of volcanic origin. Table 1 presents the coverage of the major soil and land cover classes for the Beaver Creek watershed as determined from the data sources described in Section 2.2.2. Summer precipitation during the NAM (July to September) in the watershed accounts for ~40% of the annual total (Baker, 1986), producing ~15% of the annual streamflow (Baker, 1982). The watershed is sampled by a network of ten automated rain gauges operated continuously by the Yavapai County Flood Control District and three continuous stream gauges (Dry Beaver Creek (USGS 09505350) near Rimrock, AZ, Wet Beaver Creek (USGS 09505200) near Rimrock, AZ, and Beaver Creek outlet (USGS 0950550) at Camp Verde, AZ) operated by the U.S. Geological Survey (USGS), with more limited data over 2004–2008 for the outlet site (Fig. 1). In addition, significant streamflow responses were identified at all stream gauging stations only during the summers of 2005–2007, limiting our study period to this interval.

2.2. Distributed hydrologic model and its application

2.2.1. Model description

The TIN-based Real-time Integrated Basin Simulator (tRIBS) was selected to conduct the summer season simulations in the Beaver Creek watershed. tRIBS is a spatially-explicit model of hydrologic processes (Ivanov et al., 2004; Vivoni et al., 2007). To make full use of the available geospatial datasets, tRIBS ingests terrain, soil, land cover, and meteorological conditions and resamples each to the model domain. A watershed is represented by a Triangulated Irregular Network (TIN) consisting of elevation, stream, and boundary nodes, which capture features with a reduced number of elements as compared to the original grid DEM (Vivoni et al., 2004). In tRIBS, Voronoi polygons are associated with each TIN node and serve as the finite-volume domain for water and energy balance calculations. For each Voronoi polygon, the model tracks the hydrologic response, including: (1) canopy interception; (2) evapotranspiration from bare soil and vegetated surfaces; (3) infiltration and soil moisture redistribution; (4) shallow subsurface flow; and (5) overland and channel flow (Table 2). In prior studies, tRIBS has shown good performance with respect to hydrologic data in other semiarid watersheds (e.g., Vivoni et al., 2010; Mahmood and Vivoni, 2011; Xiang et al., 2014). For this particular study, we emphasize the model ability to generate streamflow simulations at the outlet and interior locations as well as the time-averaged spatial distribution of soil moisture, runoff and evapotranspiration. Additional details on the model can be obtained from Ivanov et al. (2004) and Vivoni et al. (2007, 2010).

2.2.2. Model domain, parameterization and initialization

Spatial inputs for the Beaver Creek watershed model application include topography, soil texture, land cover and initial depth to the groundwater table (Ivanov et al., 2004). The watershed domain was delineated from a 30 m Digital Elevation Model (DEM) obtained from the USGS (Fig. 1) and converted into a TIN using the hydrographic procedure described by Vivoni et al. (2004). A stream network that matched available hydrography was included in the model domain, resulting in 76,624 Voronoi polygons or an equivalent cell size, r_e, of approximately 120 m (Vivoni et al., 2005). This