Water resources vulnerability to climate change in the Upper Santa Cruz River, Arizona

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Abstract: In the Upper Santa Cruz River episodic streamflow events recharge a shallow alluvial aquifer, which is an essential water resource for the City of Nogales and surrounding communities. The complex natural variability of the rainfall-driven streamflow events introduces a water resources management challenge for the region. In this study, we assess the climate change projections of precipitation for the Upper Santa Cruz River from eight dynamically downscaled IPCC Global Circulation Models. Two models from the University of Arizona are downscaled simulations of carefully selected high performing Global Circulation Models for the region, and the other six are selected NARCCAP simulations. Our analysis of the eight selected dynamically downscaled climate model projections indicated an increase (decrease) frequency of occurrence of dry (wet) summers. The winter rainfall projections indicated an increase frequency of occurrence of both dry and wet winter seasons, which implies lower chance for a medium winter. The projected drying summers and increased winter inter-annual variability are expected to further complicate the water resources management task.

Keywords: Climate change, NARCCAP, Santa Cruz River, Ephemeral streams, Water resources management

1 INTRODUCTION

Meeting water demands in semi-arid and arid regions is a particularly challenging task in remote communities that rely on their local resources and lack the infrastructure for multi-years’ storage. Precipitation variability in these regions often incurs long dry spells with episodic wet events that refill the reservoirs. The geographic focus of this study is the Upper Santa Cruz River (USCR) at the border of Arizona – Sonora Mexico (Figure 1). In this region the city of Nogales Arizona and surrounding communities rely on water supply from a relatively shallow and small aquifer (hereinafter microbasins) beneath the ephemeral USCR (Erwin 2007). The highly variable intermittent flow events on the USCR are the key source of recharge to the microbasins (Erwin 2007). Thus, the natural variability of the river flow and groundwater recharge are tightly linked (Liu et al. 2011; Nelson, 2010; Shamir et al. 2007).

Several studies in recent years reported changes in the hydrologic regime of the USCR, such as: reduction in summer streamflow volume and number of summer streamflow occurrences (Thomas and Pool, 2006, Shamir et al. 2007b); reduction in the duration of baseflow (Nelson,
2010), reduction in number of summer precipitation events although no indication for a change in total rainfall (Shamir et al. 2007b); and a substantial increase in the monthly variability of streamflow since the 1970s (Shamir et al. 2007b). This hydrologic regime changes further complicates the water resources management tasks. In this study we evaluate climate change projections of rainfall for this region, which unfortunately, introduce additional management challenges for the region’s water resources.

2. CLIMATE PROJECTIONS

The study region has two rainy seasons: summer (July-September) and winter (November-March). Summer storms are mainly driven by isolated convective cells of thunderstorms that produce intense short-lived rainfall events that are highly distributed in space. Winter storms which may last for few days with persistent rain over large areas, almost entirely originate from large scale low pressure frontal systems approaching from the west and southwest. These storms are strongly linked El Niño Southern Oscillation (ENSO) (Shamir et al. 2007b). Cyclonic storms caused by remnants of tropical storms over the Pacific Ocean that are capable of producing large storms over Southern Arizona seldom occur in late summer early fall. (e.g. Hirschboeck, 1985).

![Figure 1: A regional map for the study area, the black plusses represents the centroids of the selected grid cells of the UA-ATMO regional downscale model that were analyzed herein.](image)

The impact of future projected warming (Garfin et al. 2013) on the microbasins is still unclear since recharge occurs intermittently and the aquifer is relatively shaded from evaporation and transpiration fluxes. Future climate projections of precipitation in this region must include a separate analysis for the winter and summer precipitation. Garfin et al. (2013) projected increase probability for drier winter attributed to the projected widening with time of the high pressure subtropical Hadley cell, which in turn will push the jet stream, the moisture carrier for the regional winter storms, northward. The summer convective rainfall is a more challenging phenomenon to predict because its origin, frequency, and distribution are not clearly linked to larger scale regional
control synoptic conditions. The southwestern monsoonal convective storms are small scale phenomena compared to the scale resolved by the current climate models.

The inter-annual frequency and spatial pattern of the monsoon, however, is claimed to be related to the latitudinal shift in the midlevel subtropical ridge over the southwestern U.S. (i.e. Northern displacement yields wetter summer). The location of this ridge is tied to different phases of the Pacific Northern America teleconnection pattern (Carleton et al. 1990). More recent studies indicated that the North American Monsoon inter-annual variability is related to ENSO and PDO-forced atmospheric teleconnection patterns emanating from the tropical Pacific (e.g. Castro et al. 2007b) and/or antecedent land surface conditions (e.g. Grantz et al. 2007). This relationship implies that during years with anomalously high sea surface temperature in the Eastern Pacific the North American Monsoon season is delayed and shortened (Seth et al. 2011; Cook and Seager, 2012). Castro et al. (2007a, b) also found a long-term increase in the late twentieth century (1950-2002) of the diurnal cycle strength of the summer convection, which implies intensification of the thunderstorms.

2.1 Analyses of the Regional Downscaled Models

Regional Climate Model (RCM) downscaled precipitation projections for the study domain [31°N - 31.5°N, 111.5°W - 110.44°W] (Figure 1) were obtained from the University of Arizona Atmospheric Sciences Department (UA-ATMO) and the North American Regional Climate Change Assessment Program (NARCCAP). These RCM outputs were forced by Global Circulation Models (GCM) simulations using A2 emission scenario [IPCC Special Report on Emission Scenario] for the 21st century, which predicts slow economic growth and an ever-increasing population.

Because of the large spatial and temporal variability in the Southwest it is imperative to select GCMs that capture the dominant climatic processes for the region. The GCMs should at least reproduce the region’s climatology and inter-annual variability of the large-scale atmospheric circulation. In addition, it is important to select GCM models that simulate the mesoscale conditions of the monsoon ridge and Pacific-SST forced teleconnection that modulate its positioning in the early part of the summer. It is also essential to simulate the mesoscale conditions that modulate the diurnal convective summer precipitation (Castro et al. 2012).

The UA-ATMO applied the Advanced Research version (ARW) of the Weather Research and Forecasting (WRF) Model (Version 3.1) to downscale two well performing coupled models from the Inter-comparison Project Phase 3 (CMIP3) IPCC AR4 GCMs (Dominguez et al. 2010). These selected models are the UKMO-HadCM3 by the Hadley Centre for Climate Prediction and Research at the Meteorological Office in United Kingdom; and MPI-ECHAM5 from the European Center for Medium-Range Weather Forecast (ECMWF) and the Max Planck Institute. These two models were selected from twenty four IPCC CMIP3 competing models for their ability 1) to represent the observed temperature and precipitation, and 2) to simulate the large scale circulation features that drive moisture fluxes into the Southwest U.S. (Dominguez et al. 2010). The winter ENSO variability that affects the location of the subtropical jet stream and consequently winter rain in the Southwest was evaluated by looking at the models 250 mb geopotential height field (GPH). The skill of these two selected models to resolve observed warm-dry and cool-wet teleconnection patterns over the Pacific North West and Southwest US associated with El Nino and La Nina events was also confirmed by Zhang et al. (2012).

The UA-ATMO ARW-WRF downscale simulations were performed at 35 km grid spacing for contiguous Mexico-U.S domain and boundary forcing was updated in 6-hour intervals (Castro et al. 2012). The duration of the simulation are as of the available duration of the GCM forcing data; MPI-ECHAM: 1950-2100, HadCM3: 1968-2079. In following few paragraphs an evaluation of the MPI-ECHAM is discussed.
Five dominant precipitation modes from the dynamically downscaled MPI-ECHAM were calculated using Empirical Orthogonal Function/Principal Component (EOF/PC) analysis of the Standard Precipitation Index (SPI) (Castro et al. 2012; Ciancarelli et al. 2013) for the winter and summer seasons. In Figure 2 the sum of the two modes that explain the highest spatiotemporal variance for the study area are shown. The correlation between the time series of the combined PC modes and the observed rainfall from the gauge data for the winter and summer is 0.8 and 0.7, respectively and explains at least 60% of the variability for each season. The correlation maps between the combined PC time series and the dynamically downscaled SPI for both winter and summer are shown in Figure 2 (left panels). High correlation values are seen for the core monsoon region with high values for the study area.

Maps of the combined PC correlation with MPI-ECHAM Sea Surface Temperature (SST) anomaly are shown in Figure 2 (right panels). The ENSO/PDV (Pacific Decadal Variability) signal of SST appears as the notable spatial pattern associated with both winter and summer rainy seasons in the North American Monsoon region (Ciancarelli et al. 2013). Positive winter precipitation anomaly is expected during the El Niño/high PDV phase and a positive anomaly summer precipitation during La Niña/low PDV phase. The SPI-SST correlation maps (Figure 2 right panels) follow this expected large-scale SST variability pattern. Moreover, Ciancarelli et al. (2013) reported high correlation between the precipitation PC and 500 mb geopotential height for the MPI downscale, which indicates reasonable simulation of the atmospheric teleconnectivity.

To summarize it is found that both winter and summer dominant precipitation modes were generated with adequate lateral boundary conditions. The dominant precipitation from the

Figure 2: Left panel: spatial correlation between the WRF-MPI SPI combined mode and WRF-MPI SPI gridded data for summer (upper) and winter (bottom). Right panel: spatial correlation between the WRF-MPI Standard Precipitation Index combined mode and WRF-MPI sea surface temperature for summer (upper) and winter (bottom).
downscaled MPI-ECHAM simulation is matching the observed natural variability and thus its future simulation is suitable for impact assessment studies.

2.2 North American Regional Climate Change Assessment Program (NARCCAP)

NARCCAP is a multi-institutional effort to produce high resolution climate change simulations to explore uncertainties in regional scale projections of future climate and generate climate change scenarios for use in impact assessment studies (Mearns et al. 2007). The NARCCAP comprises of two phases: In phase I, dynamically downscaled simulations from meteorological reanalysis boundary conditions is performed; in phase II, similar simulation but for IPCC A2 climate projections is performed. We used NARCCAP simulations from phase II. NARCCAP used six regional climate models (RCM) to downscale four Atmosphere-Ocean General Circulation Models (AOGCM) for the historic period 1971-2000 and for projected future period 2041-2070, covering the conterminous United States and most of Canada. The NARCCAP RCM grid spacing is 50 km with 3-hour reporting intervals. The four selected AOGCMs are the Canadian Global Climate Model version 3 (CGCM3), the NCAR Community Climate Model version 3 (CCSM3), the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model version 2.1 (CM2.1), and United Kingdom (UK) Hadley Centre Climate Model version 3 (HadCM3). All four models have been considered in all IPCC assessment reports.

Assessment of the NARCCAP models for their skill in reproducing summer precipitation from the North American Monsoon system concluded that the GFDL model lacked the skill of forcing a RCM to produce realistic summer rain in the Southwest (Bukovsky et al. 2013). Thus, we decided to omit the GFDL and rely on the other three GCMs each downscaled with two RCMs (six total model simulations): WRFG-CCSM3, RCM3-CGCM3, HRM3-HADCM3, WRFG – CGCM3, RCM-CCSM and CRCM-CGCM3. The CCSM and CGCM were both reported to have dry summer biases and the HADCM3 was found to provide the most realistic boundary conditions as RCM forcing with early monsoon onset (Bukovsky et al. 2013).

3. RESULTS

Analysis of observed total seasonal rainfall from gauges yields three wetness categories for both the winter and summer seasons (i.e. dry, medium and wet). The historical frequencies of the wetness categories were determined based on analysis of inflection points on the cumulative distribution curves of the seasonal total rainfall. The frequencies of the historic wetness categories are seen in Figure 3 (left bars) for the winter and summer (left and right panels, respectively).

The eight downscaled RCM simulations were compared for their frequency of winter and summer wetness categories for the periods available from NARCCAP (1971-2000 and 2041-2070). The rainfall values of the corresponding percentiles of these observed thresholds were identified on the RCMs output for the historical 1971-2000 period. The percentiles of these thresholds values were then identified in the RCMs future projection simulation (2041-2080) to identify the projected frequency of occurrences of the three wetness categories for the winter and summer.

Figure 3 compares the results from the eight different RCMs and the historical period (left bar). The last bar is an average of the frequencies from the eight RCM models. The noteworthy conclusion from Figure 3 is that for the summer season, seven models indicated higher frequency of future dry summer and six models indicated lesser frequency of wet summer. An outlier model that showed lower and higher frequency of dry and wet summer, respectively is the UA-ATMO WRF-HAD. All eight models indicate higher frequency of dry winter and six of the models also indicate higher frequency of wet winter. Looking at the average frequencies of all the eight...
models, it is seen that on average, it is projected to have higher frequencies of dry summer and winter and, higher and lower frequencies of wet summer and winter, respectively.

Figure 3: The projected (2041-2080) frequency of wet and dry winter and summer (left and right panels, respectively). The frequency of the historical record and the average frequencies of the 8 model are also indicated.

Inspecting the WRF-MPI time series simulation of the total summer and winter precipitation demonstrates the projected changes explained above. Figure 4 shows the standardized anomaly time series of summer (left) and winter (right) precipitation from 1950-2009. The thick horizontal black lines demarcate the upper and lower tercile thresholds for the early (1950-2009) and late (2019-2080) 21st century. In summer, both the lower and upper terciles are projected to decline.

Figure 4: The UA WRF-MPI simulation of precipitation standardized anomalies (the deviation from the average divided by the standard deviation) of summer (left panel) and winter (right panel). The black solid line is the 10-year moving average and the black dots are the terciles lines during 1950-2009 and 2019-2080.
In summer, both the lower and upper terciles are projected to decline. It is seen that the lower tercile of the historic period is projected by the WRF-MPI and is projected to become the future threshold for the upper tercile of wet summers. This implies increase frequency of future dry summer, as defined by the historical record, to ~2/3rd of the years, and infrequent years with wet summer. In winter, the WRF-MPI projection shows increase (decrease) of the upper (lower) tercile thresholds which imply that the historic dry and wet frequency will increase and frequency of medium winter will decrease. In other words, based on the WRF-MPI projection, the extreme wet and dry winter will occur more frequently.

Additional analysis was performed to detect other precipitation features with clear differences between the historic and future WRF-MPI simulation spans. The only considerable detected difference between the historic and future periods is for the duration between rainfall events in summers that are categorized as dry. This implies that the projected future dry summers are dryer than the historic dry summers. This increase in the duration between storms is attributed mainly to projected delay of the monsoon onset and therefore reduction in the frequency of precipitation events. No clear differences were found for other precipitation features such as the magnitude of precipitation, distribution of storms duration and total storms quantity.

3. Final Remarks

In this study we evaluated rainfall projections for the Southwest U.S. from eight carefully selected dynamically downscaled climate models. The analysis of the climate projection was carried to identify the occurrence frequency of seasonal (summer and winter) three wetness categories. Such an analysis enables a direct link to the historical record by assuming that the future intra season rainfall characteristics, for a given wetness category, will be similar to this category at the historically observed record. A comparison between the rainfall intra season characteristics of the historic and future periods from the dynamically downscaled climate models simulations showed that for a given season and wetness category the two periods were mostly indistinguishable. The results of this intra seasonal variability comparison support the above stated assumption.

The analysis of the climate model future simulations for changes in the wetness categories indicate future projections of higher frequency of dry summer and increased inter-annual variability for the winter. Although outstanding agreement among the eight selected models supports the presented results, the pre-posed assumptions used in this study are likely to introduce additional uncertainty to the results. Nevertheless, the findings of this paper highlight the importance of water resources management that accounts for increased rainfall variability and increased future uncertainty. Our team is currently engaged in water resources study for the region that is supported by the local relevant agencies and collaborative with regional stakeholders. We plan to report results in the near future.

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