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Return levels of hydrologic droughts under climate change

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ABSTRACT

Developments in the statistical extreme value theory, which allow non-stationary modeling of changes in the frequency and severity of extremes, are explored to analyze changes in return levels of droughts for the Colorado River. The transient future return levels (conditional quantiles) derived from regional drought projections using appropriate extreme value models, are compared with those from observed naturalized streamflows. The time of detection is computed as the time at which significant differences exist between the observed and future extreme drought levels, accounting for the uncertainties in their estimates. Projections from multiple climate model-scenario combinations are considered; no uniform pattern of changes in drought quantiles is observed across all the projections. While some projections indicate shifting to another stationary regime, for many projections which are found to be non-stationary, detection of change in tail quantiles of droughts occurs within the 21st century with no unanimity in the time of detection. Earlier detection is observed in droughts levels of higher probability of exceedance.

1. Introduction

Traditional assumptions of stationarity to estimate the risk associated with hydrologic extremes such as droughts have come under scrutiny in the light of global climate change. Historically observed tail quantiles of hydrologic events and their uncertainties may undergo non-stationary changes in future because of global warming or human effects [45,53,58]. Increasing temperatures due to increased greenhouse gas (GHG) emissions are projected to intensify droughts [12] in the twenty-first century. However, only *low* to *medium* confidence is achieved for projection of hydrological extremes, because of the limitations of climate models and lack of sufficient observations at smaller scales [24]. In particular, drought events may vary considerably in time and extent [5] and such events are extreme and rare by their very nature. In order to improve drought resilience and/or for long term planning, a comprehensive assessment of changes in drought characteristics is thus necessary and challenging at the same time.

The Colorado River is one of the most important rivers of the Western United States sustaining over 30 million people and providing water to seven states of USA and the country of Mexico [44]. Persistent dry conditions are reported for the South-west USA and the Colorado River Basin [20], which are projected to intensify in the future [7]. Sensitivity of the runoff generating snowmelt processes as well as increasing water demands to changing climate conditions emphasize the need for assessment of climate change impacts in this river basin [36]. General circulation models (GCMs) provide future climate simulations for changing GHG emissions, which can be used for future drought risk assessment [6]. The low resolution of GCMs and their inability to simulate localized processes necessitate the use of a statistical downscaling model which is often used together with physically-based hydrologic models for generation of streamflow projections. Christensen et al. [9] used statistically downscaled precipitation and temperature from a multiple-member ensemble of a GCM to run the Variable Infiltration Capacity (VIC) hydrologic model and predicted decreases in mean runoff in the Colorado River Basin. However, it is recommended that the uncertainties due to lack of knowledge of physical climate and natural variability be characterized by using multiple GCMs [6]. Using mean of the simulations from multiple GCMs and scenarios, the average annual precipitation and temperature are projected to increase in this river basin, while the mean runoff is projected to decrease by 8.5% by 2050 [52]. However, these figures are only with respect to the historical simulation of the hydrologic models corresponding to climate model runs, and not with respect to the observed naturalized flows. Miller et al. [44] also use statistically downscaled precipitation and temperature to run the VIC model for getting streamflow projections in the Gunnison River which is a tributary of the Colorado River. They use these projections for comparison with

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paleoreconstruction of streamflow data in terms of regime shifts. Changes in the hydrological extremes in terms of magnitudes or quantiles of droughts with respect to those from the observed flows, and the time in future when such changes are expected, remain unexplored.

Extreme value theory (EVT) provides the theoretical basis for modeling extreme events. Non-stationary extensions to the traditional stationary extreme value models enable incorporation of effects of one or more physically-based covariates in the parameters of the statistical extreme value model. These developments in EVT are increasingly being explored to study effects of global climate change [4,26,28,29,31,57,59]. It is reported that changes in climate extremes may be more robustly detectable than changes in mean [22,46]. Non-stationary extreme value distributions can be applied to study such changes in extremes for increasing the rigor as well as for a more physically meaningful analysis [19,28]. Burke et al. [6] use the Peak-over-threshold (POT) approach of EVT to study changes in future meteorological droughts over the United Kingdom. We extend their approach to hydrologic droughts in the Colorado River to additionally report the time of detection for tail quantiles of droughts from the non-stationary drought projections with respect to the observations, considering the errors in their estimates. We seek answer to the question of how long the historically observed return levels of droughts will hold good for planning and adaptation. For example, if a drought of 100-year return period is of interest to the water resources manager, we determine whether and when the observed historical 100-year drought will cease to be a correct measure of risk based on each streamflow projection, taking into account the associated uncertainties. A similar analysis using the Block Maximum approach of EVT on the high-flow hydrologic extremes of floods is conducted by Mondal and Mujumdar [49].

In this study, we first determine appropriate statistical extreme value models for each projection based on a likelihood ratio test. Detection times are computed thereafter. A standardized drought index is defined based on 3-month accumulated streamflow in the Colorado River. A two-component non-stationary POT statistical model based on Poisson-Generalized Pareto (Poisson-GP) distribution is used to model changes in the frequency and intensity of droughts. Global mean surface air temperature, averaged over multiple GCMs, has been considered as a covariate instead of a simple time-dependence [6]. Changes in regional mean temperatures at many locations across the globe are reported to be consistent with the changes in global mean temperature [43,62].

Fig. 1 provides an overview of the steps conducted in this study. For observations as well as each of the streamflow projections, monthly flow data are first standardized to obtain a drought index based on 3-month accumulated flows. Extreme drought index values are retained using a peak-over-threshold approach. These extremes are declustered so that no two extreme values represent the same 3-month drought. Likelihood ratio test is conducted on the declustered extreme drought index and an appropriate stationary or non-stationary model is fitted to observations as well as each of the projections. If the observations are stationary (in this study it is found to be so, as shown later), a constant drought return level would be obtained from the stationary statistical Poisson-GP model fitted to the observed extreme declustered drought index series. Similarly, for stationary projections, a constant drought return level is obtained. For non-stationary projections, transient 'effective' drought return levels [28] would be obtained. These effective return levels are conditional quantiles whereby the 'return level' is allowed to vary from one time period to the next holding the probability of occurrence constant [28,53]. For example, the 100-year transient effective return levels are the quantiles at each time step corresponding to probability of exceedance $p = 1/100 = 0.01$. This definition of transient return levels has been used in earlier studies for risk communication in a non-stationary world [6,15,25,28] and though these quantiles may not correspond to any one particular return period, they do represent meaningful quantities to illustrate the effects of non-stationarity. Projected return levels are compared with the observed return level through a detection test. Each of these steps is described in details in the 'Methodology' section below. The remainder of the paper is organized as follows – Section 1 describes the observed and model data used, while Section 2 provides details on the methodology. The results are discussed in Section 3 and summarized in Section 4.

2. Observed and model data

Natural streamflows (without the effects of regulations) are considered in this study as our focus is on changes in drought quantiles due to global climate change. The projected monthly flows have been obtained from the streamflow projections dataset prepared by the U.S. Bureau of Reclamation [17,52] for 1950–2099, at 195 sites spanning the Western United States, publicly available at http://www.usbr.gov/WaterSMART/wcra/flowdata/ (accessed on May 18, 2013). These flow data are obtained from the simulations of the physically-based Variable Infiltration Capacity (VIC) macroscale hydrological model [41,64] run with statistically downscaled bias-corrected [38] meteorological forcings from the 112 projections from the GCMs participating in the World Climate Research Program's Coupled Model Intercomparison Project 3 (WCRP/CMIP3). The 112 projections are obtained by simulations from different runs of 16 GCMs with the three emission scenarios – A1B, A2 and B1 [23].

Bias Corrected Spatial Downscaling (BCSD) method is used as the statistical downscaling model to obtain precipitation and temperature at $1/8^\circ \times 1/8^\circ$ latitude-longitude grid across the Western United States covering the major Reclamation basins. Runoff, surface and subsurface, simulated by the VIC at $1/8^\circ \times 1/8^\circ$ latitude-longitude grid, are hydraulically routed to each of the 195 locations. Using a statistical downscaling technique in combination with a physically based hydrologic model is a standard practice for impact assessment studies, and both the BCSD downscaling technique and the VIC hydrologic model are well-known methods [52].

The BCSD statistical downscaling model in conjunction with VIC has been used to study hydrological changes in the Western United States also by other studies [8,14,40,44]. There are other studies [7,13] who use the downscaling method of constructed analogues (CA) in conjunction with VIC, though the results of BCSD and CA are mostly reported to be quantitatively similar [39]. We choose Colorado River at Lees Ferry (Lat 36° 51′ 53″, Long 111° 35′ 15″ W) location in the state of Arizona, with a drainage area of approximately 111,800 sq miles as it has a large drainage area and has long observed naturalized flow data available. The streamflow projections are obtained without additional efforts on VIC model calibration (for improving the existing level of calibration); however, the streamflow data that we have used can be used for comparing changes in flow characteristics with those of the past so as to at least gain an insight into the nature of such changes [14,44]. Moreover, for large basins at monthly and larger scales, the VIC model is able to reproduce streamflows reasonably well [52].

Observed monthly naturalized streamflows in the Colorado River at Lees Ferry for the period 1906–2010, obtained from the United States Geological Survey (USGS) observed gage data, are obtained from the website of the Upper Colorado Regional Office of the United States Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html). Global average surface air temperature (*tas*) anomalies, obtained from the mean of multiple GCMs, are used as covariate. Annual multi-model average detrended *tas* anomalies relative to the 1980–1999 mean from