Diagnostic Analysis of Summer Precipitation and Streamflow in the upper Gila River basin

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Contents

1. Introduction

This paper presents a statistical analysis of variability and trends of warm season precipitation and streamflow in the upper Gila River basin, southwestern New Mexico. The analysis is the second of a 2-part series of papers assessing low-flow months in the upper Gila basin in terms of observed streamflow and precipitation, and projections of these variables out to year 2050 using climate model simulations. The first paper, entitled "Trends and Variability in Summer Precipitation and Streamflow in the upper Gila River basin" (Gutzler 2015, henceforth cited as G15) presented fundamental statistics of climate change and climate variability in summer months in the basin, focused on flows at USGS gage 09430500, located on the Gila River near Gila (Fig. 1).

The early months of the summer comprise the low flow season in the upper Gila as shown in climatological hydrographs (Gutzler 2013; Horner and Dahm 2014; Garfin et al. 2014). Flows reach a minimum after snowmelt runoff occurs in late winter and spring, and before the summer monsoon season has recharged the basin with intermittent, relatively high intensity rainfall events (Gutzler 2013). Low flows limit ecological productivity in and around the Gila River, and therefore also place limits on potential water withdrawals from the river. The papers cited above were prepared for the purpose of providing guidance on projected future flows in the Gila River, for use regarding decisions on water allocations and potential diversions within New Mexico related to the 2004 Arizona Water Settlements Act. This paper adds to the analyses of low flows in the early summer, and attempts to assess confidence in future projections yielded by climate models forced with increasing greenhouse gas concentrations?

What is the basis for determining confidence in projections? By definition, we cannot directly validate model forecasts of hydroclimate changes that are projected to occur decades into the future. We can, however, check to see which components of model projections are observable as trends in recent data. For example, temperature trends are clearly observable across southwestern North America in data from recent decades (Gutzler and Robbins 2011; Gutzler 2013; and many other studies).

This observation by itself does not prove that the observed warming in the upper Gila basin was caused by increasing greenhouse gas concentrations; addressing that issue

would require a formal model-based attribution study, such as the broad assessment carried out for continental-scale climate change by the Intergovernmental Panel on Climate Change (IPCC 2013). And the absence of an observed trend in recent decades, by itself, would not disprove the likelihood of a trend becoming established in the 21st Century. However, for this study I will assess the uncertainty in projected climate changes to be smaller, and confidence in the likelihood of a projected change to be higher, if I can detect evidence of at least the beginning of a change consistent with the projection in recent observed data.

In G15, projected flow changes were found to be different in the two low-flow months of June and July. In June, prior to the current climatological onset of the summer monsoon, monthly average flows are projected to decrease in simulations generated by the U.S. Bureau of Reclamation (Reclamation 2011). Decreasing flow in June was found to be distributed across low and high-anomaly months, i.e. the entire distribution of projected future flows in June decreases relative to the distribution of June monthly flows in the current climate as simulated by Reclamation's coupled climate-hydrology models. July projected flows exhibit very little change averaged over the Reclamation simulations, except in the high-flow tail of the distribution where flows increase significantly.

In section 2 of this report, June and July flows are assessed in terms of the two principal statistical determinants of interannual streamflow variability: persistence of flow from the previous month and concurrent precipitation. These predictors are used to assess the relative importance of processes that determine low flows in these two months. In terms of these processes, we find that June flows are principally determined by flows from the preceding month, with precipitation variability playing a much less important role in modulating streamflow. On the other hand, precipitation variability in July is greater, and the residual importance of snowmelt runoff less important, so that monsoon-related precipitation in July is the principal determinant of the volume of streamflow at the Gila gage. The difference in the relative importance of these streamflow predictors has implications for assessing confidence in projected trends in low flows in future decades, as will be discussed in the synthesis of results in Section 4.

Before interpreting confidence in mean flow projections, Section 3 considers extreme daily flows in the observational record relative to monthly mean flows. The purpose of this

section is to provide a basis for interpreting interannual statistics of monthly average flows in terms of extreme events, motivated by projections that suggest an increase in extreme high flow events in a future warmer climate, even if monthly mean flows change little or decrease (Garfin et al. 2014). We find that variations of observed monthly mean flows provides a very good proxy for the entire distribution of daily flows in June and July, and that year-to-year variations in extreme daily flows scale linearly with corresponding interannual variations in monthly means.

Section 4 presents a synthesis of the results, along with a discussion of the factors that promote relatively more or less confidence in climate model based projections of future flows in June and July. The overarching goal of the paper is to attempt to reduce uncertainties in summer low-flow projections. The analysis in Sections 2 and 3 achieves this goal in part, adding to confidence in projections of diminished flow in June. However we will conclude that uncertainties in the future of low flows in July remain high, and that the approach taken here does not confirm the likelihood of high extreme flows if mean flows do not also increase.

The report concludes with a summary of principal results in Section 5.

2. June and July hydrologic trends and variability

a) Observed variability in low-flow months

June and July exhibit very similar low-flow statistics in the observational record at the Gila gage (G15, figures 5 and 6), with monthly mean flows averaging approximately 50 cfs in each month. The average hydrograph at the Gila gage decreases through most of June, bottoms out at the end of June, and on average begins to rise in July toward a secondary maximum driven by the onset of the summer monsoon (G15, figure 2). The extreme high end of the distribution of monthly mean flows in July exhibits an increase in the second half of the observed record that is not evident in June. Despite the similarities in the statistics of mean flows in June and July, relationships between discharge (Q) at the Gila gage and other climate variables, such as antecedent snowpack, antecedent streamflow, and concurrent precipitation, are very different in these two low flow months. In this subsection we present a description of these hydroclimatic relationships. Subsection (b) then examines

whether simulated flows reproduce the relationships observed in data. This examination is used to assess confidence in projected flows derived from coupled models in the Bureau of Reclamation simulations.

Anomalously low or high flows are quite persistent from May to June. A scatter plot of May and June streamflow anomalies at the Gila gage (Fig 2a) shows the tight relationship between anomalies. Although the flow in May, during the declining period of annual snowmelt runoff, is much larger than in June (note different scales on the x- and y-axes in Fig. 2a), anomalously low or high flows in May are reliably followed by anomalous flow with the same sign in June. The autocorrelation of monthly average flow anomalies from May to June in the observational record is r = 0.92. This value means that fully 85% (r^2) of the interannual variance of June monthly flow is accounted for by the preceding monthly mean, i.e. anomalous flows in May are highly likely to be followed by similar anomalies in June (confirming what one sees in Fig. 2a).

This high level of monthly persistence in Q is not seen a month later, from June into July. As shown in Fig. 2b, low or high flow anomalies in June provide no reliable indication of anomalous flow in the subsequent July. The autocorrelation between June and July flows is r = 0.24, so that only about 5% of July variance of monthly means is accounted for by the previous month's flow in June.

Another plausible relationship is between monthly precipitation and discharge, as illustrated by the scatter plots in Fig. 3. For purposes of seasonal forecasting monthly persistence of flows and concurrent monthly precipitation are two of the leading terms in the operational regression formulae used by the U.S. Natural Resources Conservation Service (NRCS) to generate operational water supply outlooks (Garen 1992).

Precipitation in June is often quite low, seen as the cluster of points with mean values less than 0.5" in Fig. 3a. Interannual variations in June precipitation are not significantly correlated with June streamflow (r = 0.13). In contrast, July precipitation amounts tend to be higher, such that no values of July precipitation in Fig. 3b are less than 1.0". Monthly average flow at the Gila gage in July is significantly correlated with concurrent monthly precipitation in the upper basin (r = 0.60). This correlation value exceeds the threshold for

rejecting a null hypothesis of zero correlation at the 5% confidence threshold, assuming each year is independent.

So interannual variability in June streamflow at the Gila gage is tightly associated with flow anomalies from the previous month. We interpret this result as indicating that extreme low flows in June monthly average data are a function of deficient snowmelt runoff, as reflected in low May streamflow. Precipitation in June, before the onset of the monsoon, is too sparse to have a major effect on June monthly average flows.

On the other hand, July monthly mean flows are nearly independent of flow conditions in the previous month of June. Instead, July flows vary from year to year based on whether the early weeks of the monsoon season provide abundant rains to generate streamflow (or not, in relatively low precipitation years).

Furthermore, June climate conditions in the upper Gila basin do not provide straight-forward guidance for July anomalies -- at least based on the straightforward month-to-month streamflow autocorrelation statistics considered here. There is a continuing discussion in the published literature concerning the seasonal predictability of summer monsoon rains (e.g. Gutzler and Preston, 1997; Castro et al. 1999; Griffin et al. 2013; and others). Resolving this debate is beyond the scope of this report, but demonstrated seasonal prediction skill of summer precipitation anomalies remains low. For the purpose of the present analysis, the important point is that July streamflow anomalies are signifcantly dependent on July precipitation anomalies (Fig. 3b). Such anomalies are difficult to simulate reliably, and uncertainty in projecting summer precipitation into the future remains high. For these reasons, corresponding uncertainty in July streamflow in the upper Gila basin also remains high.

b) Model-projected variability in low-flow months

The four panels in Fig. 4 provide a comparison of model simulations from the Bureau of Reclamation (2011) -- the same model simulations assessed in previous studies by Gutzler (2013) and G15 -- with the observed correlation results presented in Figs. 2 and 3. The objectives here are to examine how closely the BoR models reproduce observed persistence of monthly streamflow, and observed correlation between streamflow and precipitation. The model results are divided into two sets: first, we examine model output

for the current climate (1951-2000), which in principle should be directly comparable to the observed results. Then, the model-generated correlations are calculated over the first half of the 21st Century (2001-2050) to see how the results change as temperatures increase in the model simulations.

The persistence (autocorrelation) statistics of monthly mean flow from May to June, and from June to July, calculated separately for 39 independent simulations for the 1951-2000 period, is illustrated in Fig. 4a, the upper left panel in Fig. 4. Each model result is shown as a dot (the lines connecting the dots are for visualization only and have no significance). The observed autocorrelation of 0.92 in June (from Fig. 2a) is indicated along the y-axis as a green arrow. None of the 39 simulations for June reproduces an autocorrelation as high as the observed value.

July results, shown in red on the same figure, are much closer to the observed value of persistence from the previous month (0.24, shown as the red arrow). There is considerable scatter among model results, but most models exhibit a small but positive autocorrelation from June to July, roughly in line with the observed value.

Model results corresponding to Fig. 3, showing the correlation between monthly mean streamflow and precipitation in simulations of the 1951-2000 period, are shown in panel 4c (the lower left panel). Model simulations consistently describe a positive correlation, as expected, and they consistently show that the correlation is greater in July (red) than in June (green). Both of these results are also qualitatively consistent with observations. However the coupling between precipitation and streamflow is much tighter than in observations, for both June and July.

Furthermore, the reversal from June to July from a persistence-dominated streamflow regime to a precipitation-dominated regime is captured in the models. The model simulations systematically overestimate the correlation between precipitation and streamflow found in observations, but otherwise capture many features of the hydro-climatic regime of the upper Gila basin in the low flow season.

Moving from the left-hand panels to the right-hand panels, it can be seen that the general character of these correlation relationships does not change much in the warmer climate of the early 21st Century. The spread from model to model of the correlation

results increases in both months, which has the effect of making June and July results somewhat less separable than in simulations of the late 20th Century climate.

In summary, observations suggest a distinct difference between the processes responsible for low flows, and interannual variations of those low flows, between June and July. Streamflow in June is much more closely tied to antecedent flow conditions associated with the end of the snowmelt runoff season; July is much more closely tied to the precipitation at the beginning of the summer monsoon. Model simulations capture this difference at least qualitatively, and with considerable spread, but generally tie streamflow to precipitation more closely than observations indicate in both months.

3. Sub-monthly extreme flows

Most of this results used in this report, as well as the results reported in the previous paper in this series (G15), are based on monthly average streamflow and weather variables. Time-averaged variables are generally considered to be more representative of climatic variability and trends than instantaneous or daily variables. However the observed record of daily streamflow can be examined to assess how representative the time series of monthly mean flows are for characterizing extreme daily flows during the month, a critical concern for water management. Garfin et al. (2014) reported simulations of projected flow in summer months in which the trend in the monthly mean flow (downward) was different in sign from the trend in high-end extreme flows (upward). They attributed the difference in sign to the projection of higher, short duration extreme precipitation events in simulations of future warmer climate in the upper Gila basin.

Scatter plots of June and July observed flows at the Gila gage are shown in Figure 5. The x-axis in each plot denotes the monthly mean flow for each June or July month in the historical record, plotted against the corresponding low flow (green) and high flow value (red) for the same month. Low flows are defined as the 10th percentile value of daily flows for the month, i.e. the daily flow exceeded by 90% of daily values that month. This metric essentially describes the three lowest daily flows in a 30-day month. High flows are similarly defined in terms of the 90th percentile, i.e. the daily flow exceeded by 10% of daily flows during each month (the highest three daily flows).

Figure 5 indicates that variations in the monthly mean from year to year are highly correlated with corresponding interannual variations in daily extreme flows. The relationship between mean and extreme flows is nearly linear for both months, and for both high and low flows.

The results suggest that the monthly mean serves as an excellent proxy for extreme daily flows at the Gila gage in historical data. When monthly mean flows are anomalously low or high, then the extreme flows at both ends of the distribution of daily flows within the months also tend to be low or high, following a straightforward linear relationship as illustrated in Fig. 5. These calculations do not show any evidence for the existence of a discrepancy between fluctuations in extreme flows and mean flows, as shown by Garfin et al. (2014) in high resolution projections of flows at the Gila gage.

Figure 6 shows the same data points plotted in Figure 5, but in time series format. As would be expected from results already shown, the years with anomalous median, high or low flows vary up and down together. The time series in Fig. 6 provide a complementary picture to the corresponding time series of monthly mean flows presented in G15 (Figures 5a and 6a). In G15 it was shown that distributions of monthly and daily flows at the Gila gage widened (i.e. flows have become more variable) in the second half of the data record, during the decades when temperature increased significantly in the upper Gila basin.

The increased variability in flows from the first to the second half of the historical record occurs in association with warmer summer temperatures, and when most precipitation is convective and therefore dependent on local moisture and energy. Although we cannot prove cause and effect from data analysis, the increase in variability of daily streamflow driven by convective precipitation, correlated with a warming trend in temperature, is consistent with physical expectation. This aspect of observed variability is also consistent with high-resolution regional climate model projections discussed by Garfin et al. (2014).

However, the observed data do not show that the increased variability in the data includes decoupling between mean and extreme flow variability, characterized by an increase in extreme high flows even while mean flows are not increasing. The data do not indicate any trend toward lower or constant mean flows in conjunction with more variable

flows. Consistent with the approach to uncertainty described in the Introduction, the results in Figs. 5 and 6 do not add to confidence in a future projection of higher extreme flows even in years with lower mean flows.

4. Discussion: Assessing and reducing uncertainties in low-flow month projections

There are several characteristics of model projections that we can use to assess confidence in those projections. Consistency among many model projections is one such characteristic. The fact that Reclamation (2011) used many separate large-scale climate models in their West Wide Water Assessment allows consistency to be examined across many simulations that are at least somewhat independent. All the models are forced with the same future time-varying greenhouse gas concentrations (the so-called A1B scenario), and the same downscaling and land surface model are applied to the climate variables. Consistency does not guarantee veracity, but it is an indication of some degree of robustness in the response of simulated climate to anticipated forcing.

For example, <u>all</u> models simulate a warming trend in future climate in response to the prescribed, significant increase in greenhouse gases. A warming trend of some magnitude makes physical sense, given the climate community's firm understanding of how Earth's greenhouse effect works. Higher temperatures in the 21st Century represent a projection that we can make with high confidence.

A second characteristic of the model projections that relates to confidence is the presence of a consistent signal in recent decades, a period during which temperatures have been observed to rise significantly (Gutzler 2013; Garfin et al. 2013; and many other studies). If model projections suggest a particular change in precipitation, streamflow, etc. in response to increasing greenhouse gases, then confidence in the projections increases if we observe some semblance of the projected change during the past few decades when greenhouse gas concentrations are known to have increased and temperatures have been observed to rise.

Neither of these considerations is necessary or sufficient to prove the inevitability of a particular model projection, and observed changes do not provide much guidance concerning the magnitude of a future projected change. But assessing model consistency,

and comparing with recent observed changes, provides a useful basis for assessing confidence, and thus potentially reducing uncertainty. Our results indicate that low flow projections in June should be considered separately from low flows in July.

June flow anomalies are highly persistent from the previous month of May. As discussed at length by Gutzler (2013), flow projections for May and the entire snowmelt runoff season are for diminished flows associated with rising temperatures, diminished snowpack, and earlier melt. Increasing temperature and declining snowpack are the most robust components of hydroclimatic projections associated with 21st Century climate change. Hence the analysis here, tying June flow to that of May, adds one more diagnostic layer of confidence to projections of lower flow in June.

As discussed in G15, the projected change in average flow in June between the 1951-2000 and 2001-2050 averaging periods, averaged over all 39 simulations considered in these reports, is about 7% in mean flow and 8% in median flow. This is about the same value as the percentage decrease in future decades for the earlier snowmelt runoff season estimated by Gutzler (2013). The specific decrease in flow is sensitive to the length of the averaging period used, and to the rate of Greenhouse gas increase prescribed to occur in the future. With these caveats in mind, the present analysis would add the low-flow month of June to the earlier snowmelt runoff months as likely to suffer diminished flows in future decades.

July flow is nearly uncorrelated with preceding June flow, in both observations and Reclamation (2011) model simulations. Summer precipitation, to which observed July streamflow is correlated (and even more so in simulations) as shown in Section 2, remains difficult to simulate and uncertain in projections. Therefore the very modest projected changes in July streamflow (G15, Fig. 8) remain uncertain. Reclamation models do not simulate any change in mean July streamflow that can be confidently asserted.

Some model-based studies of monsoonal rainfall in a warmer climate have suggested that, even if total summer precipitation does not change, monsoon onset could shift to a later date (Seth et al. 2011; Cook and Seager 2013). If this were to happen, then July could take on hydroclimatic characteristics more like June in the current climate, which would reinforce projections of decreasing precipitation and streamflow in July. However, applying

the same philosophy of assessing confidence in projections by confirming projected climate signals in recent data, Gutzler and Keller (2012) found that monsoon onset across the Southwest has exhibited a weak tendency to start earlier, not later, in recent years. The model-based projection of a shift toward later monsoon onset in a warmer climate is not confirmed in recent observations, and so is considered to be a highly uncertain projection.

Data quality presents a serious impediment to comparing model results with observations. Specifically, summer precipitation is exceptionally challenging to determine from sparse observations across a large area of complex terrain, such as the upper Gila basin. A detailed assessment of precipitation quality is beyond the scope of this paper. However it is quite plausible to assume that some of the difference in the correlation between observed and simulated streamflow and precipitation (Fig. 4), which is systematically lower in observations, could be due to errors in spatially interpolating rainfall across the upper Gila basin.

In the CMIP3-based simulations considered in this study, extreme high monthly flows are projected to decrease in June, but increase in July. Observed extreme daily flows (the lowest and highest 10% of daily flows within a month) were shown in Section 3 to scale linearly with variations of monthly mean flow. This finding provides some justification for the simple procedure of scaling the entire distribution of daily flows based on projected monthly flows by a constant, for the purpose of estimating future daily flows in the summer low-flow season.

The results of this study add confidence to projections of diminishing flows across the entire distribution of daily flows in June, because the trends in projected flow distributions are consistent with the observed trends in flows in recent decades. However we find that extreme high flows in July, which increased in the second half of the historical record, did so in conjunction with increased monthly median flows during that time(G15, Fig 7; this study, Fig. 5), whereas projections show increases in extreme high flows while median flows (averaged over a broad suite of models and simulations) decrease.

The increase in extreme high monthly flows in July is associated with those models that demonstrate wetter conditions in July in the warmer projected future climate. Given the wide diversity of projected July precipitation among the various models, and the close

correlation between July precipitation and concurrent July streamflow, the enhanced variance of projected flows in July illustrates the continuing uncertainty in projecting summer monsoon precipitation and associated streamflow in the upper Gila River.

5. Principal conclusions

* As shown in Gutzler (2015), the seasonal hydrograph of flow on the upper Gila River exhibits its lowest flow in months of June and July.

* The two low-flow months exhibit markedly different covariance relationships with other climate variables in historical observations, suggesting that June and July should be considered separately for the purpose of assessing future flows. Streamflow in June is highly correlated with flow in the preceding month of June, indicating that June flows are strongly tied to the late weeks of snowmelt runoff. Streamflow in July is nearly uncorrelated with June flow, instead being dependent on precipitation during the month. So streamflow in July is not directly tied to snowmelt runoff, but is instead dependent on the early weeks of summer monsoon rainfall.

* Coupled climate-hydrologic models implemented by the U.S. Bureau of Reclamation (Reclamation 2011) qualitatively capture the observed difference in covariance relationships between June and July in simulations of the historical time period. Quantitatively, the persistence of observed flows from May to June is underestimated, and correlations between streamflow and precipitation are overestimated. The comparison between models and observations regarding streamflow and precipitation must be tempered by a caveat regarding uncertainties in calculating spatially averaged observed precipitation across the upper Gila basin.

* In observations, year-to-year changes in monthly mean flows in both June and July scale linearly with corresponding changes in the upper or lower 10% of daily flows during the month. No significant nonlinearities are found in either upper or lower extreme flows, relative to interannual variability in the mean.

* The results presented here <u>add</u> to confidence in projections of diminished flow at the Gila gage in future decades in <u>June</u>, as presented by Garfin (2014) and G15. As discussed in G15, the projected change in average flow in June between the 1951-

2000 and 2001-2050 averaging periods, averaged over all 39 simulations considered in these reports, is about -7% in mean flow and -8% in median flow. This projected decrease is quantitatively similar to the decrease found in earlier snowmelt runoff months (Gutzler 2013).

* Models and observations do not provide clear guidance for projected changes of Gila River flows during the latter half of the low-flow summer season. Projections of increased extreme high flows, despite possible decreases in mean flows, are not suggested by analysis of recent observations using the statistical techniques applied to data and model output in this paper. However precipitation extremes in July increase in projections, driving in increased values high-flow months in July (in some simulations), despite the absence of an overall upward trend in flow averaged over all model simulations. The present analysis suggests that projection of future July precipitation and streamflow remains highly uncertain, with the possibility of increased variability of heavy precipitation and high flow events.

6. References

Castro, C.L., T.B. McKee, and R.A. Pielke Jr., 2001: The relationship of the North American Monsoon to tropical and North Pacific sea surface temperatures as revealed by observational analyses. *Journal of Climate* **14**, 4449-4473.

Cook, B.I., and R. Seager, 2013: The response of the North American Monsoon to increased greenhouse gas forcing . *Journal of Geophysical Research* **118**, 1690-1699.

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson and M.K. Doggett, 2008: Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous united states. *International Journal of Climatology* **28**, 2031-2064.

Garen, D.C., 1992: Improved techniques in regression-based streamflow volume forecasting. *Journal of Water Resources Planning and Management* **118**, 654-671.

Garfin G.A., A. Jardine, R. Merideth, M. Black and S. LeRoy, eds., 2013: *Assessment of Climate Change in the Southwestern United States: A Report Prepared for the National Climate Assessment.* Southwest Climate Alliance, Island Press, Washington, DC.

-----, H.-I. Chang and M. Switanek, 2014: Climate and hydrology of the upper Gila River basin. Chapter 3 in *Gila River Flow Needs Assessment* (Gori et al. 2014, cited below), p. 40-79.

Gori, D., M.S. Cooper, E.S. Soles, M. Stone, R. Morrison, T.F. Turner, D.L. Propst, G. Garfin, M. Switanek, H. Chang, S. Bassett, J. Haney, D. Lyons, M. Horner, C.N. Dahm, J.K. Frey, K. Kindscher, H.A. Walker and M.T. Bogan, 2014: *Gila River Flow Needs Assessment.* A report by The Nature Conservancy, 515 pp. [obtained online August 4, 2014, at http://nmconservation.org/Gila/GilaFlowNeedsAssessment.pdf]

Griffin, D., C.A. Woodhouse, D.M. Meko, D.W. Stahle, H.L. Faulstich, C. Carrillo, R. Touchan, C.L. Castro, and S.W. Leavitt, 2013): North American monsoon precipitation reconstructed from tree-ring latewood. *Geophysical Research Letters* **40**, 954–958.

Gutzler, D.S., 2013: Streamflow projections for the upper Gila River. Report submitted to the New Mexico Interstate Stream Commission, 39 pp. Final version dated December 10, 2013. [http://nmawsa.org/ongoing-work/streamflow-projections-for-the-upper-gila-river-considering-climate-change/draft-stream-flow-projections-for-the-upper-gila-river/view]

-----, 2015: Trends and variability in summer precipitation and streamflow in the upper Gila River basin. Report submitted to the New Mexico Interstate Stream Commission, 39 pp. November 2, 2015.

-----, and J.W. Preston, 1997: Evidence for a relationship between spring snow cover in North America and summer rainfall in New Mexico. *Geophysical Research Letters* **24**, 2207-2210.

-----, and S.J. Keller, 2011: Observed trends in snowpack and Spring season soil moisture. *New Mexico Journal of Science* **46**, 169-182.

-----, and T.O. Robbins, 2011: Climate variability and projected change in the western United States: regional downscaling and drought statistics. *Climate Dynamics* **37**, 835-849.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis.* Working Group I Contribution to the Fifth Assessment Report of the Intergovernmenal Panel on Climate Change, Cambridge University Press, 1535 pp.

Pascolini-Campbell, M.A., R. Seager, D.S. Gutzler, B.I. Cook and D. Griffin, 2015: Causes of interannual to decadal variability of Gila River streamflow over the past century. *Journal of Hydrology* **3**, 494-508. [http://www.sciencedirect.com/science/article/pii/S2214581815000178]

Reclamation, 2011: West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Down-scaled Surface Water Projections. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver CO, 122 pp.

Seth, A., S.A. Rauscher, M. Rojas, A. Giannini, and S.J. Camargo, 2011: Enhanced spring convective barrier for monsoons in a warmer world? *Climatic Change* **104**, 403–414.

Figure 1

Figure 1. Map of the upper Gila basin, adapted from USGS site location metadata (http://waterdata.usgs.gov/nwis/nwismap/?site_no=09430500&agency_cd=USGS). The gray pointer near the bottom of the plot indicates the location of the Gila gage (USGS gage 09430500), which is the principal streamflow analysis point for this study. The gage elevation is 4655 ft ASL, with an upstream contributing drainage area of 1864 mi^2.

Figure 2

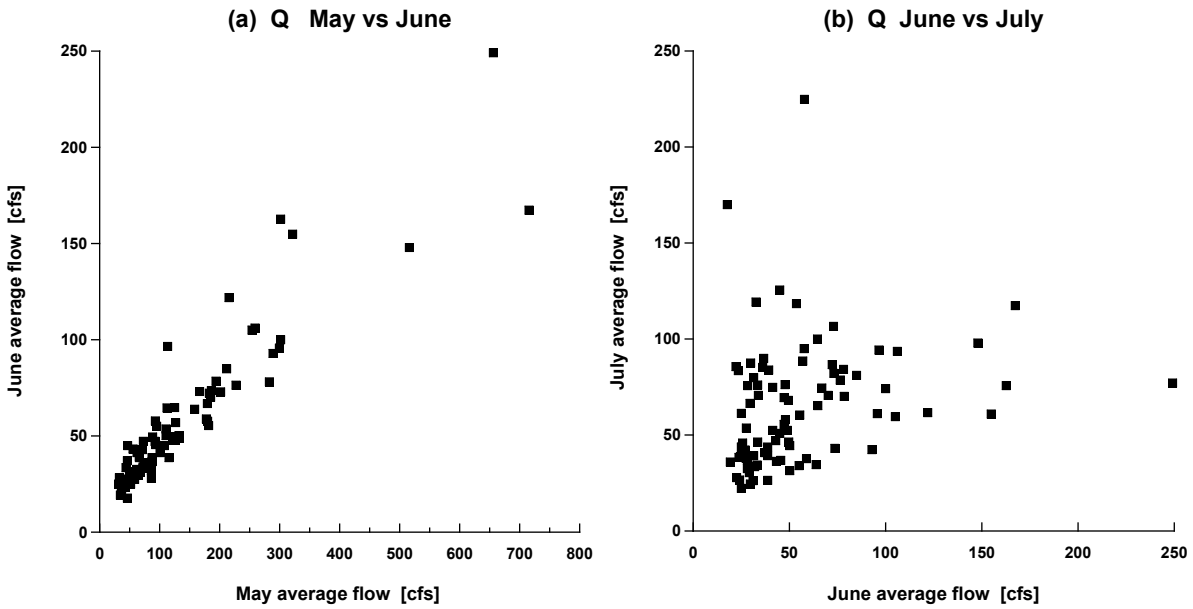

Figure 2. Scatter plots illustrating the persistence of monthly mean flows at the Gila gage (USGS gage 09430500, shown in Fig. 1) during the low-flow season. Each point represents the flow at the Gila gage (cfs) for a particular year for pairs of successive months.

(a) May-June persistence: x-axis denotes May monthly mean flow, y-axis denotes the subsequent June monthly mean flow. Autocorrelation r(May,June) = 0.92

(b) June-July persistence: x-axis denotes Junemonthly mean flow, y-axis denotes the subsequent July monthly mean flow. Autocorrelation r(June,July) = 0.24

Figure 3

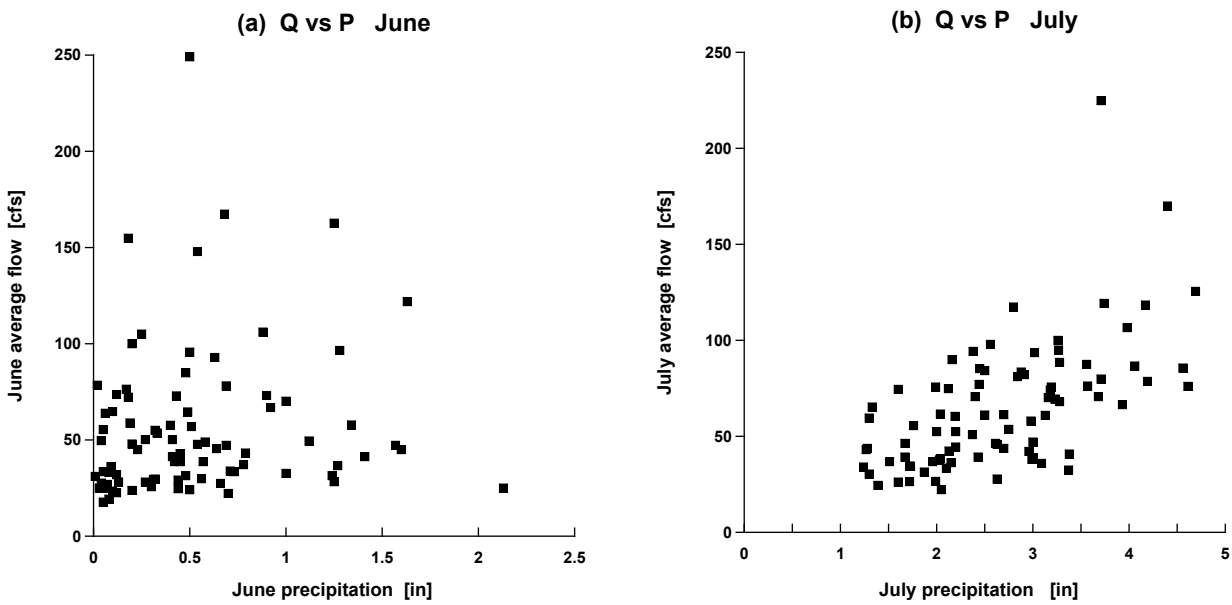

Figure 3. Scatter plots illustrating the covariance of monthly mean flows at the Gila gage with simultaneous precipitation in the upper Gila basin during the low-flow season. Each point represents the flow at the Gila gage (cfs) and monthly precipitation (in) for the month of

(a) June r(precipitation, streamflow) = 0.13
(b) July r(precipitation, streamflow) = 0.60

Figure 4

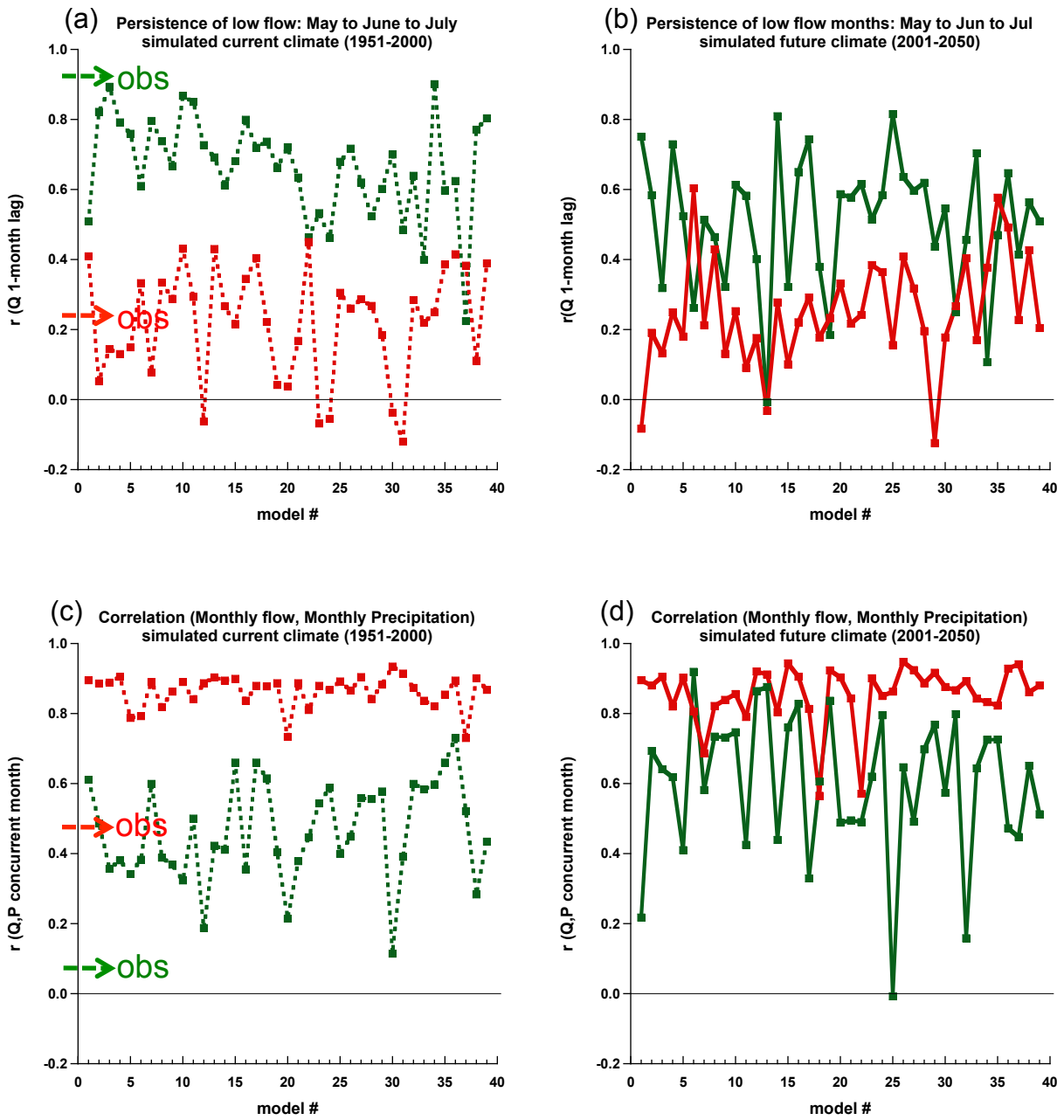

Figure 4. Comparison of 39 simulations of coupled climate-hydrologic variability in the upper Gila basin, carried out by the U.S. Bureau of Reclamation (2011). The top two panels show the one-month autocorrelation of flow at the Gila gage between May and June (green squares), and June to July (red squares), for simulation periods **(a)** 1951-2000 **(b)** 2001-2050

The bottom two panels show the simultaneous correlation between monthly anomalies of streamflow and precipitation in June (green squares) and July (red squares), for simulation periods **(c)** 1951-2000 **(d)** 2001-2050

Correlations derived from observations (see Figs. 2 and 3) are denoted by dashed arrows in **(a)** and **(c)**.

Figure 5

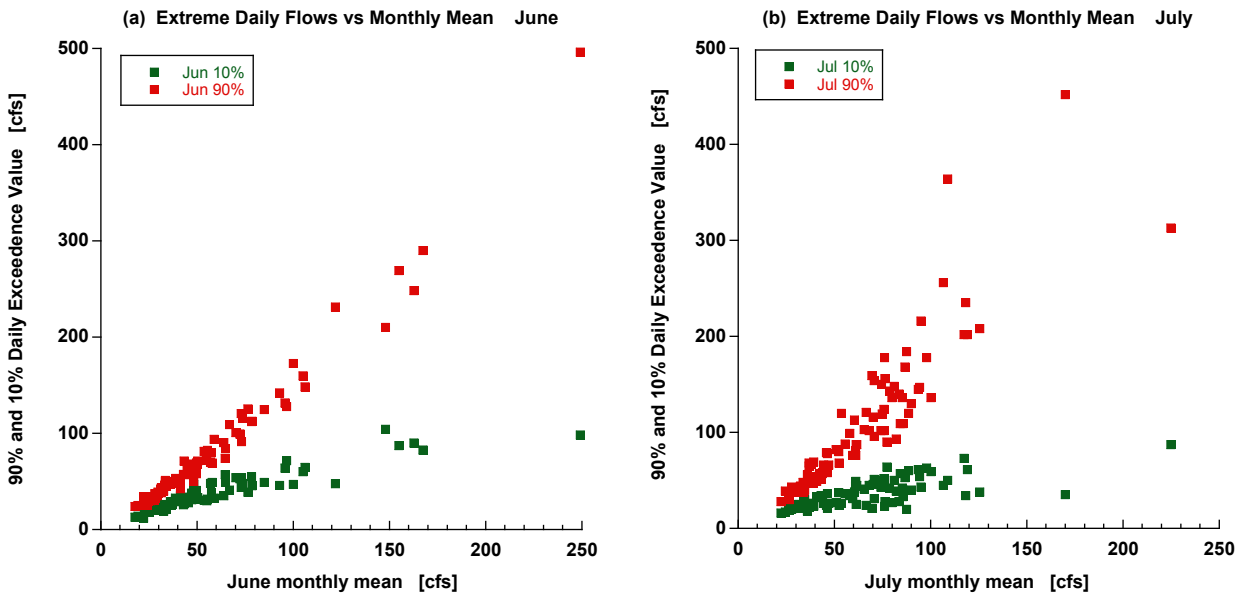

Figure 5. Scatter plots illustrating the correspondence between monthly mean flow (cfs) at the Gila gage in

(a) June **(b)** July

with the value of the 10th percentile of daily flows (low flows, green dots) and the 90th percentile of daily flows (high flows, red dots) for the same month.

Figure 6

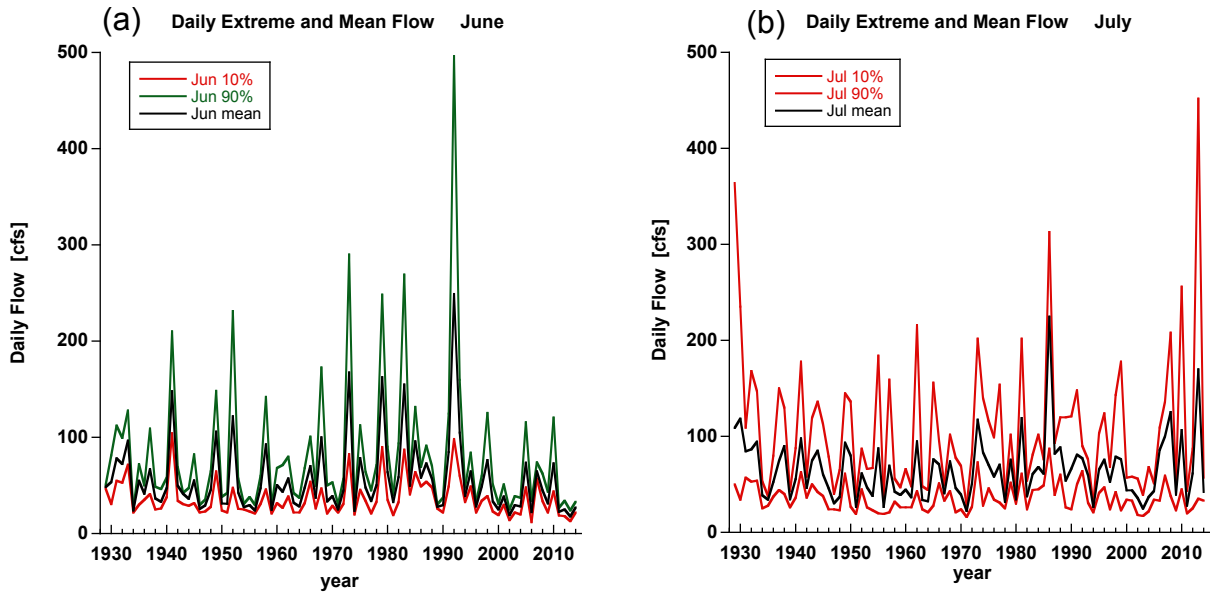

Figure 6. Time series representation of the same data shown in Fig. 5, illustrating the correspondence between monthly mean flow (cfs) at the Gila gage in

(a) June **(b)** July

with the value of the 10th percentile of daily flows (low flows, bottom line) and the 90th percentile of daily flows (high flows, top line) for the same month.