25: Modeling Hydrological Extremes in the Colorado River Basin at Various Watershed Scales.

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I. Background and Motivation

The Colorado River Basin (CRB) is a major water source for the southwestern U.S. that has experienced substantial warming, interannual climate variations, and extreme hydroclimate events in the past century. Observations suggest that climate change has amplified plant water stress and shortened growing seasons through changes in snowpack and soil moisture. Less is know about the modulating role of watershed scale-dependencies and their variable site and regionals climate regimes.

In this study we utilize a hydrologic model and a standardized drought indexing approach to address :

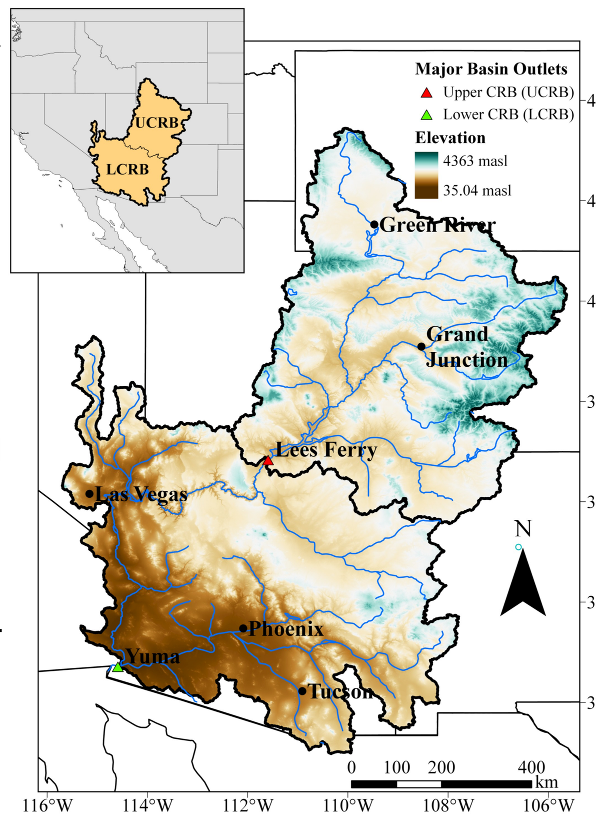

Figure 1. Phoenix study domain and the NLCD land Cover .

1. How do meteorological droughts vary in magnitude, frequency, and relative timing across CRB subwatersheds?
2. How quickly and to what degree do these droughts lead to agricultural droughts?
3. Have these responses changed throughout recent years and how differently do these responses vary within and between subbasin CRB regions?

II. Model and Climate Forcings (1976-2005)

Hydrologic Model:

We use the Variable Infiltration Capacity (VIC) model, release 5.1 (Fig. 2, up), a macroscale, distributed land-surface model, to simulate the full water-energy balance across the CRB domain.[6,9] We model at the 1/16° spatial resolution and at the daily time step. We apply recent modifications including a "clumped" vegetation scheme (Figure 2, bottom) to more properly account for bare soil in arid and semiarid ecosystems.[2]

Forcing Datasets:

We obtained datasets from Livneh et al. (2015) of gridded (1/16th degree) daily precipitation, temperature, and windspeed observations (1976 to 2005). We then use the Meteorology Simulator (Metsim), release 1.1 to estimate unobserved daily variables (short- and long-wave) and disaggregate all daily variables to hourly.[1-3]

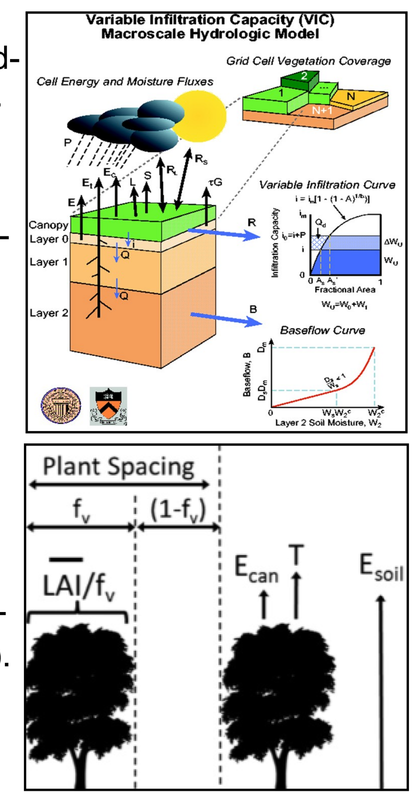

Figure 2. VIC hydrology model (top) and (bottom) the schematic of clumped vegetation scheme.

III. Watershed areas and Timeseries Aggregations

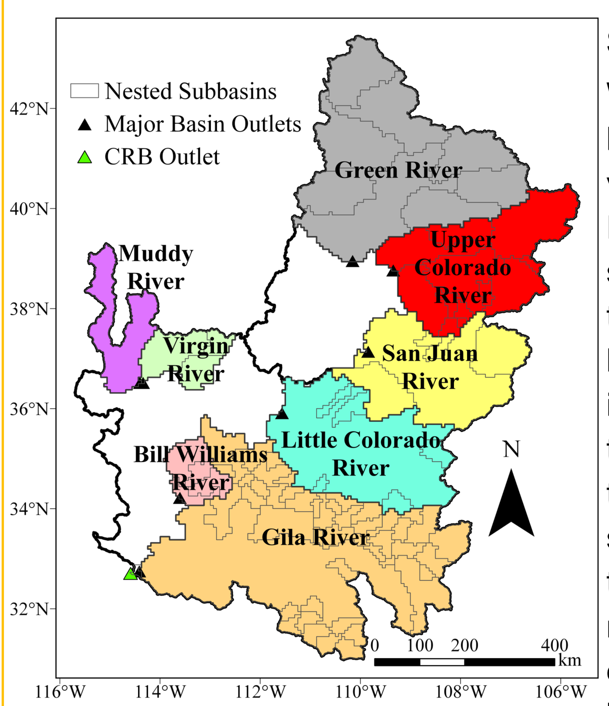

Figure 3. Major basin areas, outlets, and nested basins.

Spatial mean timeseries:

We delineated 8 major and 77 nested basin areas (Fig. 3) using National Elevation Dataset products (USGS, 2016; Fig. 1). In order to assess watershed scale dependencies, we (1) computed the spatial mean timeseries across the basin areas of daily meteorological forcings and simulated hydrological timeseries including mean air temperature (TA; [°C]) and total precipitation (P), snow water equivalent (SWE), soil moisture (SM), runoff (Q), and evapotranspiration (ET; all [mm]). We then aggregated each daily basin timeseries to monthly and mean annual timescales.

IV. Drought Indices and Event Identification

Standardized Drought Indices

We computed Standardized Precipitation and Soil Moisture Indices (SPI, SSI) from the subwatershed monthly P and SM timeseries to characterize meteorological and agricultural droughts in each basin. We used the **Gringorten plotting position formula** (Eq. 1) to estimate the empirical quantile values (Pr) of P or SM summed across a 3-month moving window:[5,7,8]

$$\Pr(x_i) = \frac{i - 0.44}{n + 0.12} \qquad \text{Eq. 1}$$

x P or SM value (current + prior 2)
i Rank of x value
n Number of values (months)

We then transformed the quantile values using the **inverse of the standard normal distribution** to derive the monthly SPI and SSI timeseries.

Drought Event Definition

We identified drought event initiation (DI) when SPI or SSI is -1.0 or less, and termination (DT) when SPI or SSI are positive (Fig. 4).[7,11]

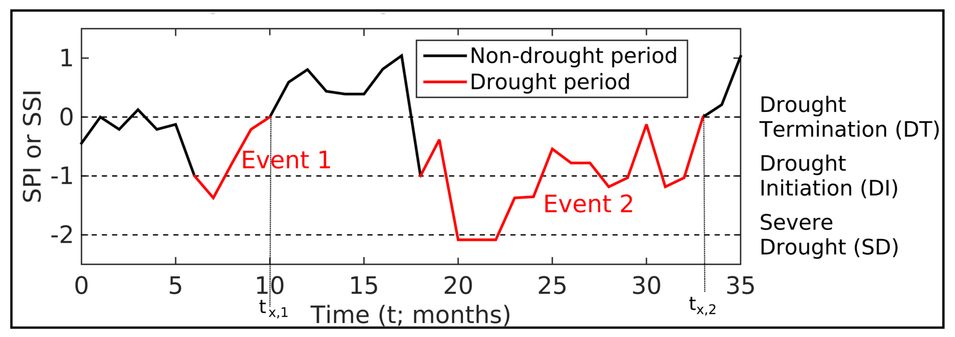

Figure 4. Criteria used to identify drought periods in monthly SPI or SI timeseries.

V. Comparisons of Water Balance and Drought Timing

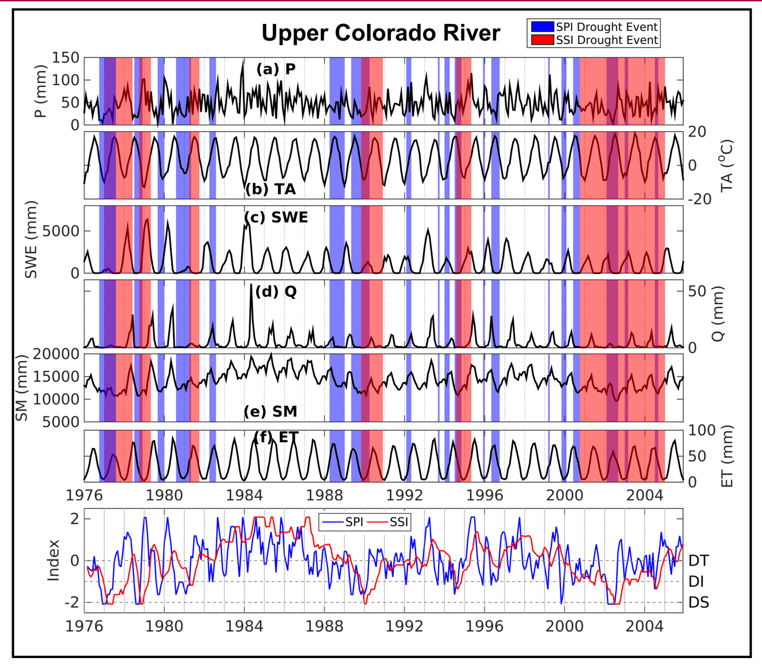

Figure 5. Spatial mean monthly water balance (top) and (bottom) monthly SPI and SSI (3-month scale) timeseries s across the Upper Colorado River.

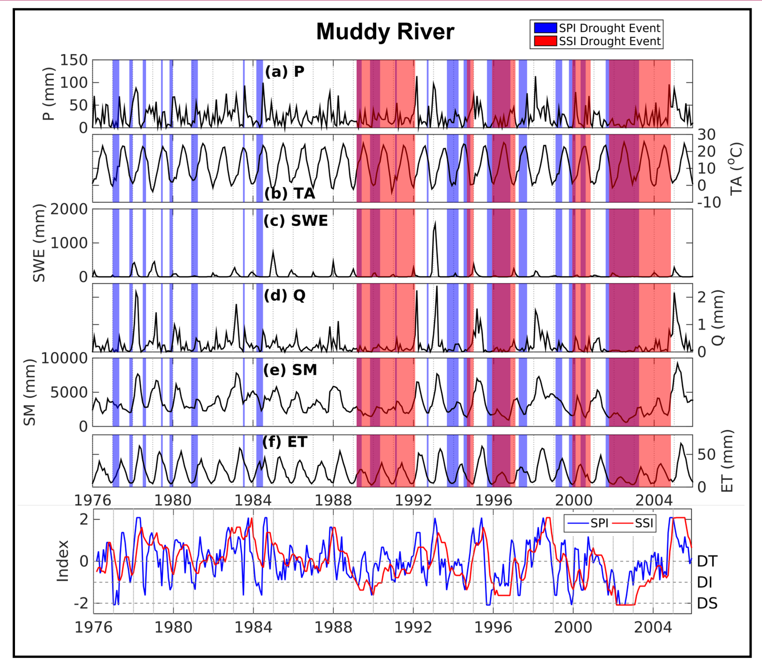

Figure 6. Spatial mean monthly water balance (top) and (bottom) monthly SPI and SSI (3-month scale) timeseries across the Muddy River.

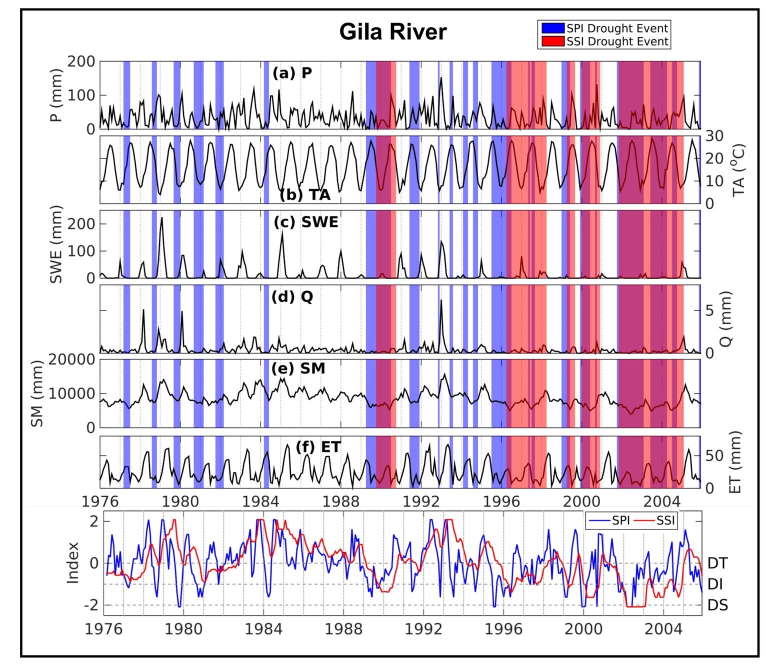

Figure 7. Spatial mean monthly water balance (top) and (bottom) monthly SPI and SSI (3-month scale) timeseries across the Gila River.

Evapotranspiration Comparisons

- The Upper Colorado (CO) River has higher snow water equivalent (SWE), which enhanced total soil moisture (SM) and evapotranspiration (ET) as compared to the Gila and Muddy Rivers (Figs. 5-7).
- With generally less available moisture in the Gila and Muddy Rivers, ET rates are generally more susceptible to declines during SPI and/or SSI droughts in the Muddy and Gila Basins, which could be due to lesser SWE (Figs. 6,7).

Drought Timing in the First Decade

- Although the Upper CO and Muddy Rivers both experienced a severe SPI drought (SPI < -2) in 1976, subsequent SSI drought only occurred in the Upper CO (Figs. 5,6).
- SWE appears to dictate SSI drought timing in the Upper CO (Fig. 5): (1) higher antecedent moisture delay the start of SSI droughts following SPI droughts, and (2) SSI droughts terminate with troughs in SWE.

Drought Timing in the Last Decades

- The Muddy River experienced an SSI drought immediately with SPI droughts in 1990 (Fig. 6).
- Due to higher antecedent moisture conditions, the Gila River did not experience SSI drought until after several months of this SPI drought (Fig. 7).
- Despite decreases in SPI drought length, the Upper Colorado experienced a multi-year SSI drought beginning in 2001 (Fig. 5).

VI. Spatial comparison of Decadal Drought Magnitudes

Drought Magnitude and Decadal Computations

For each basin timeseries of SPI and SSI droughts, we computed the drought event magnitude (DM; [months]) as the positive sum of SPI or SSI values (Eq. 2):[11]

$$DM = -\left(\sum_{t=1}^{t_x} SPI_t\right) \qquad \text{Eq. 2}$$

We summed DM values across 1976-1986 and 1995-2005 for each major and nested basin drought timeseries (Figs. 9,10). We also computed the mean annual precipitation (MAP) and temperature (MAT) anomalies across two periods (1976-1986, 1995-2005) as the difference between the MAP or MAT in either period and that of the entire the 30 year record (Fig. 8; Table 1).

Major Basin Comparisons

MAP decreased and MAT increased across all basin regions, and thus expectedly SPI and SSI DM increased for most major basin areas. The Gila River had the biggest decrease in MAP and as a result the biggest increase in SPI DM.

Despite a decrease in MAP, the Upper Colorado River experienced a decrease in SPI DM yet still higher SSI DM. This further suggests that the increase in SSI DM in the Upper Colorado River could be due to increases in MAT and decreases in SWE.

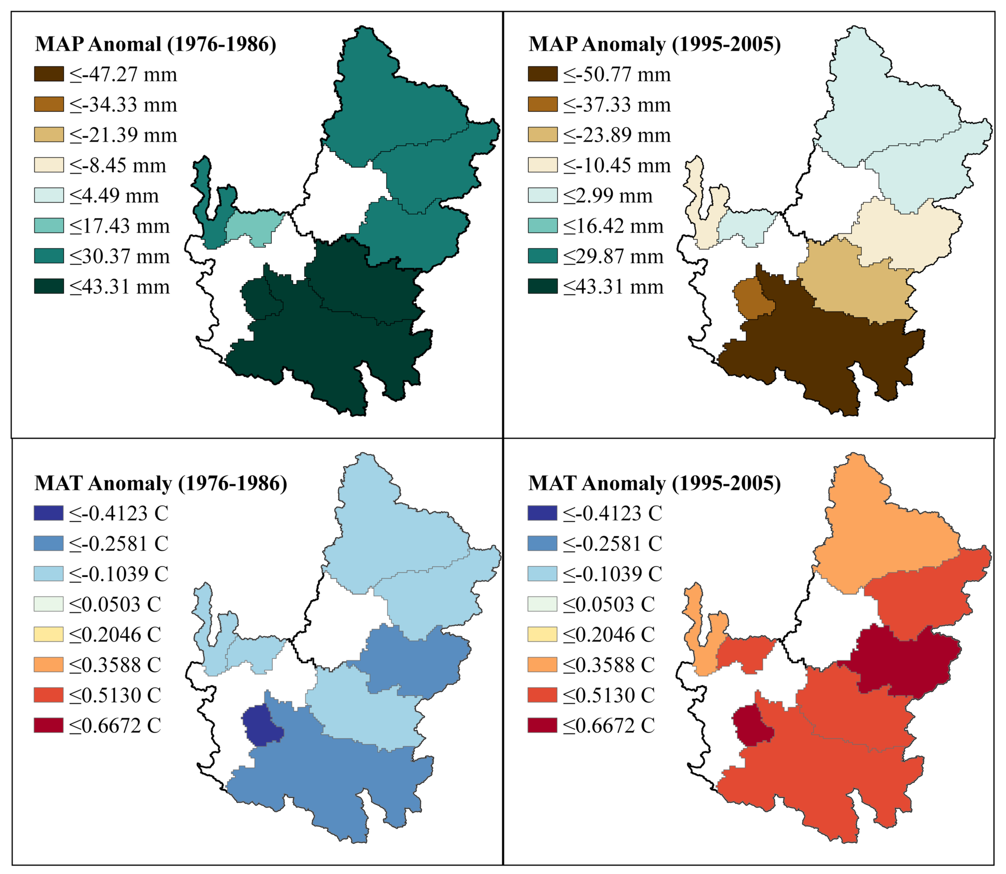

Figure 8. (Top) Mean annual precipitation (MAP) and (bottom) temperature (MAT) anomalies for (1976-1986, 1995-2005) as compared to the climatological mean values (1976-2005).

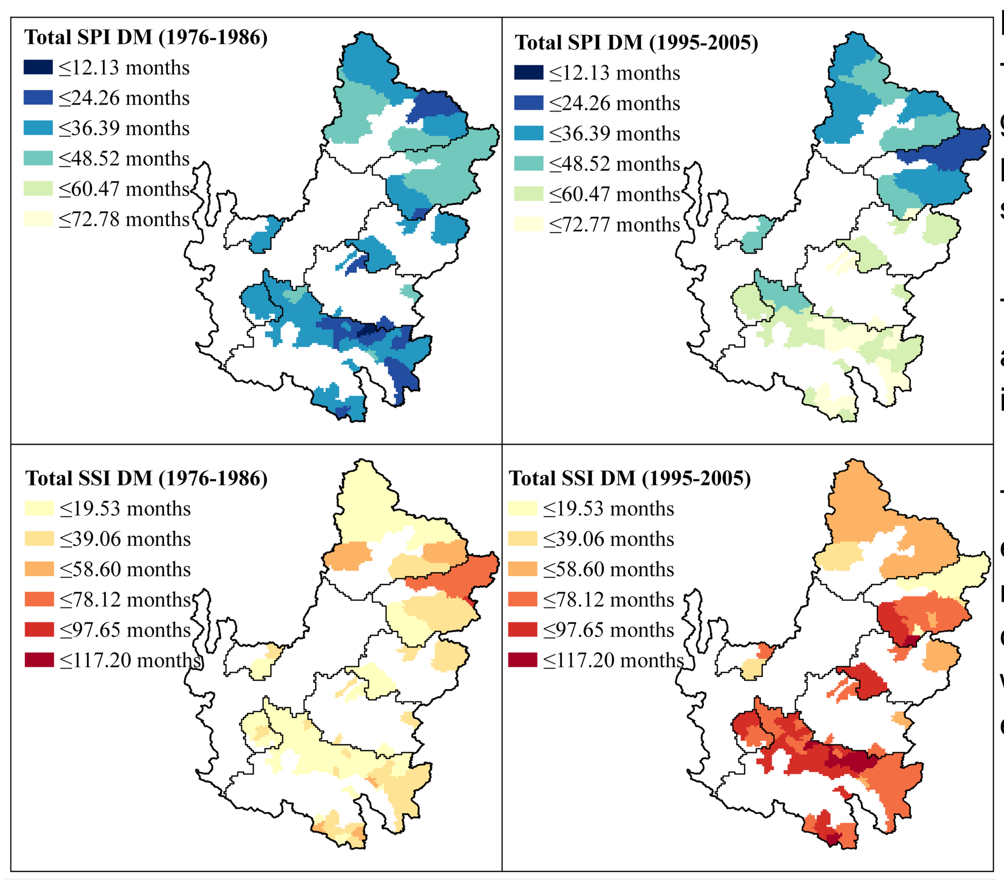

Figure 10. (Top) Total SPI and (Bottom) SSI Drought Magnitudes of all drought events in 1976-1986 and in 1995-2005.

Nested Basins

Total SPI and SSI DM are generally higher when computed at the nested basin scale.

The greatest changes in DM are again generally located in the Gila River basin.

The nested basins at higher elevations in the Upper Colorado River experienced decreases in SPI and SSI DM, whereas the lower elevations experienced increases.

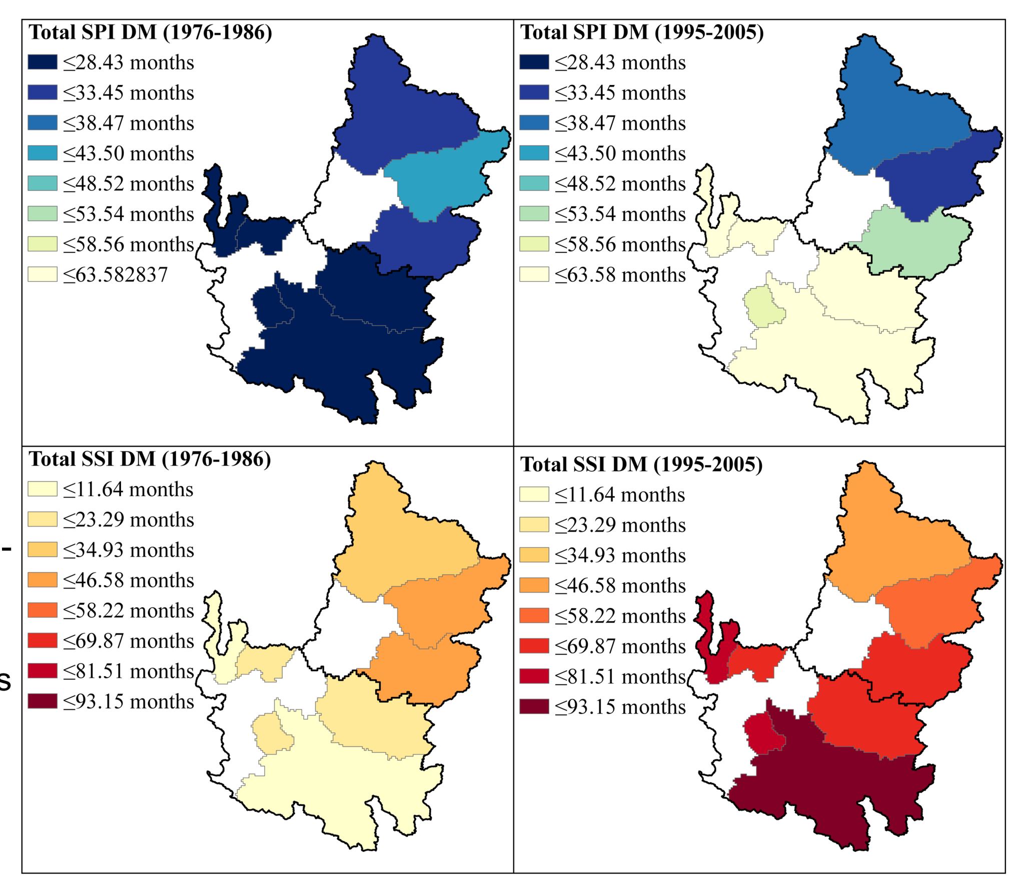

Figure 9. (Top) Total SPI and (Bottom) SSI Drought Magnitudes of all drought events in 1976-1986 and in 1995-2005.

VII. Conclusions and Next Steps

- All regions of the CRB experienced combined increases in mean annual precipitation and decreases in mean annual temperature across the timeperiod.
- While total SPI magnitude show consistent increases, SPI drought lengths did not increase everywhere in the basin. Despite these differences, total SSI drought magnitude did increase across major basin regions.
- Comparisons of monthly water balance and drought timeseries between the three basins reveal that SSI drought was more probable during longer SPI droughts, occurring more readily with drier antecedent conditions.
- Lengthening of SSI drought despite shortening of SPI drought in the Upper Colorado River suggest a strong role of snowpack and melt timing to delay and terminate SSI drought.
- Not all nested basin regions within this basin displayed the same SPI and SSI drought magnitude changes over time. This suggests a strong role that basin scale in modulating the impact of climate change, but further work is needed to explore the timeseries across a larger range of nested basins.
- In future work we will further examine these relationships at seasonal and annual timescales to help elucidate potential rippling effects of extremes across seasons and any variations in these responses within hotter and drier years.
- We will also look to fitting joint distributions to drought indices as measured from both meteorological, soil moisture, as well as streamflow and evapotranspiration to explore concurrent drought events and their variations across historic and future periods.

VIII. References

1. Bennett et al. 2018: UW-Hydro/MetSim: Version 1.1.0 (version 1.1.0), Zenodo, doi:10.5281/zenodo.1256120.
2. Bohn et al. 2013. Agric. For. Meteorol., 176, 38-49.
3. Bohn et al. 2018. [Data set], Zenodo, doi: 10.5281/zenodo.1402223.
4. Diamond, H. J., et al., 2013. Bull. Am. Meteorol. Soc., 94, 485-498.
5.Gringorten 1963. J. Geophys. Res. 68: 813-814. doi:10.1029/JZ068i003p00813.
6. Hamman et al., 2018. Geosci. Model Dev., 11, 3481-3496.
7. Hao Z., AghaKouchak A., 2013. Advances in Water Resources, 57, 12-18, doi: 10.1016/j.advwatres.2013.03.009.
8. Hao Z., AghaKouchak A., 2014. Journal of Hydrometeorology, 15, 89-101, doi:10.1175/JHM-D-12-0160.1.
9.Liang et al., 1994. J. Geophys. Res. Atmospheres, 99, 14415-14428.
10.Livneh et al., 2015. Nature Scientific Data, 2, 150042, doi: 10.1038/sdata.2015.42.
11.McKee et al., 1993. Eigth Conference on Applied Climatology, AMS, Anaheim, CA.
12. USGS, 2016. Online from https://www.usgs.gov/core-science-systems/ngp/tnm-delivery.