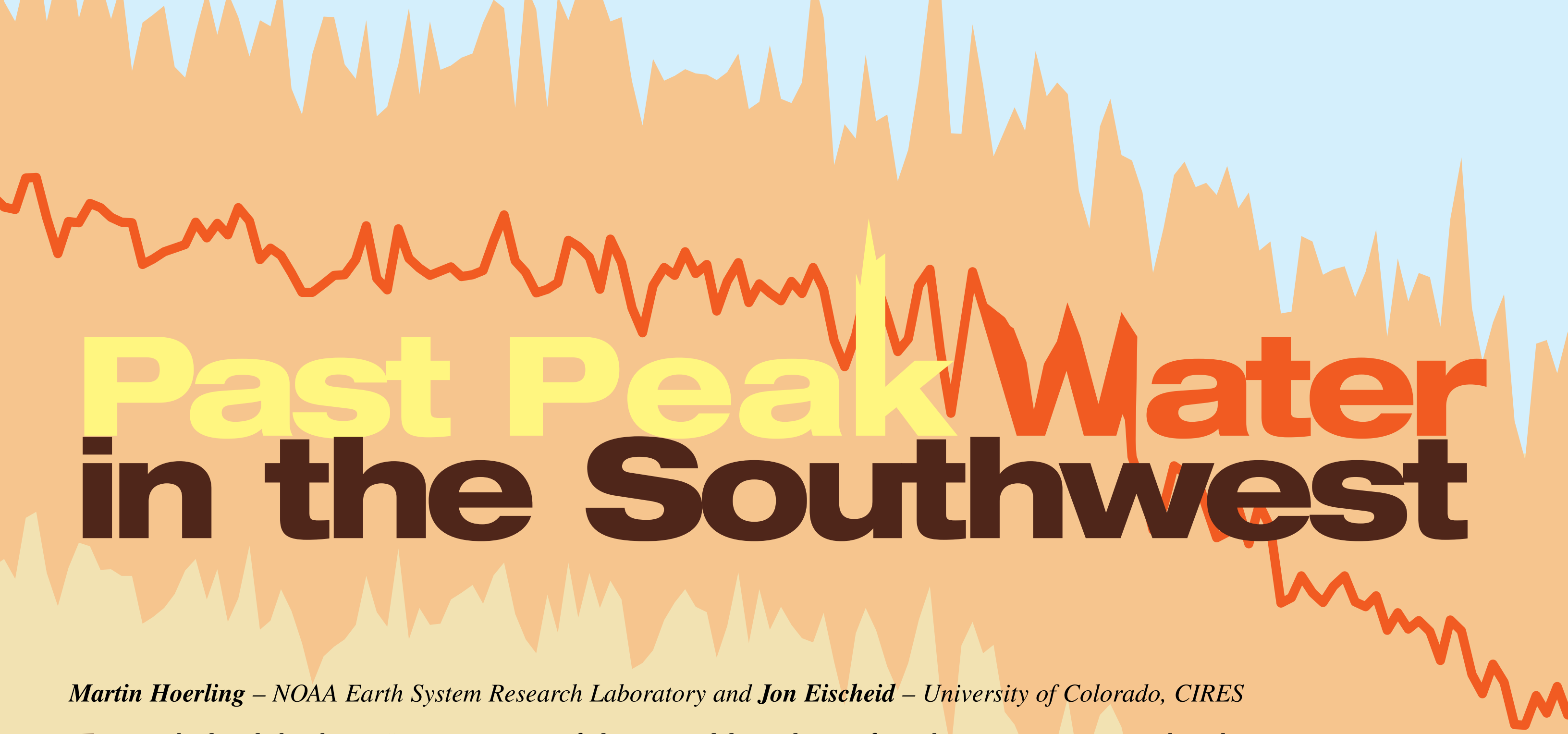

Past Peak Water in the Southwest

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Nobody relishes being "past peak" anything. Whether it's the prime of our human existence or the prime of Nature's abundance, the notion of having less rather than more is often vehemently denied. But demand growth in the face of production and storage decline has severe consequences, especially when existing uses already consume the available supply.

The lifeblood of the Southwest is the Colorado River, which is increasingly impacted by climate forces not previously experienced. The recent drought prompts concern among water users and water stewards alike, and requires the scientific community to probe whether a sustained threat is rising to our already perilous moisture balance. The consensus of the Intergovernmental Panel on Climate Change (IPCC, 2001) affirms that Earth's atmosphere is accumulating unprecedented quantities of carbon dioxide that are now causing detectable increases in surface air temperature.

Is this ongoing drought an early warning sign of something other than the historical norm, and the gateway to a future climate with more severe drought hazards? What is known about the sensitivity of moisture conditions in the Southwest to a changing climate? To seek answers to these questions, we have undertaken a systematic analysis of a new suite of climate model simulations from the arsenal of tools contributing to the 2007 IPCC Fourth Assessment Report (AR4). What is the news for the Southwest?

> *Even several of the wetter runs yield increasing drought due to the overwhelming effect of heat-related moisture loss.*

A New Drought Study

A common practice in drought monitoring is to derive a meteorological quantity known as the Palmer Drought Severity Index (PDSI; Palmer 1965). The index calculates the cumulative effects of precipitation and temperature on surface moisture balance. Water storage is solely derived from a two-layer soil system, with no explict accounting for deep groundwater or water in manmade surface storage. Drought develops when evapotranspiration exceeds the supply available from precipitation and soil moisture relative to a region's "normal" water balance. The index ranges from -4 (extreme drought) to +4 (extreme moistness).

Reservoir storage is key for assessing water supply during the course of a year in the Southwest, and is not included in a PDSI drought monitor. However, when monitoring drought conditions on annual time scales, streamflow is strongly correlated with annual PDSI. The relationship between the annual virgin flow (the estimated flow of the stream if it were in its natural state and unaffected by the activities of man) at Lees Ferry, Arizona, and the PDSI averaged over the upper Colorado Basin drainage is

$$FLOW = A_o + (A_1 \times PDSI)$$

for FLOW greater than the estimated basal flow of 3 million acre-feet (maf). Using data from 1895-1989, the linear regression coefficients are

$$A_o = 14.5 \text{ maf}, A_1 = 1.69 \text{ maf}.$$

During the 95-year reference period, annual PDSI explains 63 percent of the annual river flow variations at Lees Ferry.

Post-1989 data offer an independent period to confirm applicability of the above relation for predicting Lees Ferry flow. This period is one of warming temperatures, allowing us to test the prediction equation's fidelity in an environment of climate change. For 1990-2005, PDSI predicts 85 percent of the recent yearly fluctuations of flow at Lees Ferry, including the low flow regime during the recent drought.

To determine the probable hydrologic consequences of future climate change, the above formula was used to downscale future PDSI to Lees Ferry streamflow. The monthly PDSI was calculated for each of 42 climate simulations spanning 1895 to 2060, using multiple runs of 18 different coupled ocean-atmosphere-land models. The models were forced with the known changes in atmospheric constituents and solar variations from 1895-2000 and a business-as-usual assumption for future carbon emission after 2000.

A Drastic Change in the Character of Drought

Sustained drought of severe intensity (PDSI < -3) occurred during 1953-1956, an event rivaled during 2000-2003. The average annual Lees Ferry flow was only 10 maf during both events, but the recent drought bears different properties than its predecessor. In particular, abnormally high temperatures have been more prevalent during the 2000-2003 drought, with the West nearly 1°C warmer than during the 1950s drought.

Climate simulations of PDSI for two near-term 25-year periods (2006-2030 and 2035-2060) show an increase in drought severity (relative to their 20th century "normals") that occurs in lockstep with surface warming (see figures, above right). Little net change in precipitation occurs in the average of all models, though variability among the simulations is considerable. Nonetheless, even several of the wetter runs yield increasing drought due to the overwhelming effect of heat-related moisture loss. The Southwest appears to be entering a new drought era. In the 20th century, drought was principally precipitation driven, and enhanced by temperature. Indications from the simulations are that a near perpetual state of drought will materialize in the coming decades as a consequence of increasing temperature.

To place these probable changes into context, projections for the next quarter century paint a sober landscape in which average PDSI equates to the 2000-2003 drought conditions. This occurs as the consequence of surface water loss due to increased evapotranspiration owing to an average 1.4°C warming (relative

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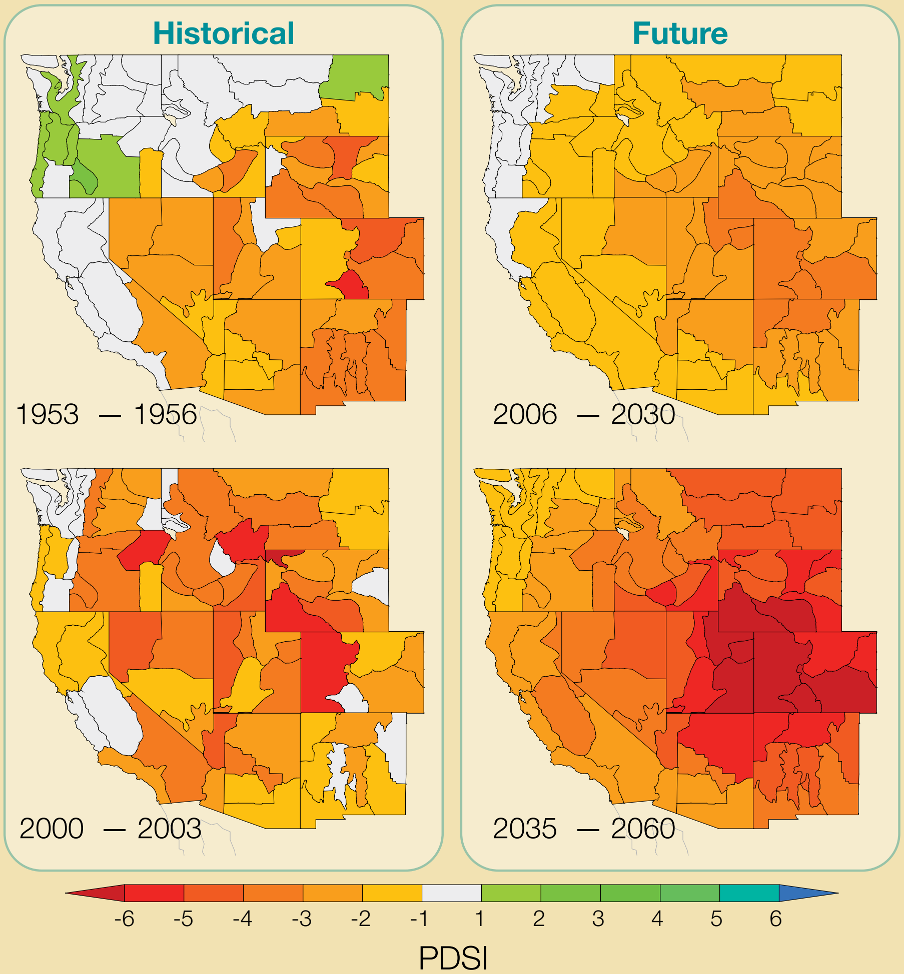

Palmer Drought Severity Index (PDSI). Values less than -3 denote severe drought conditions. Left panels illustrate the 4-year average drought conditions experienced during the 1950s drought and the recent drought. Right panels are future projections of the PDSI based on 42 simulations conducted to support the Fourth Assessment Report of the IPCC. By about 2050, average moisture balance conditions will mimic conditions experienced only rarely at the height of the most severe historical droughts.

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to 1895-2005) in the Colorado Basin. The subsequent quarter century (2035-2060) is projected to undergo a similar incremental warming: an average 2.8°C over the Upper Colorado. This drives the Palmer Index down to drought severity rarely witnessed during the 20th century.

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What are the implications of intensified aridity for Colorado River flow? Downscaling the simulated PDSI to Lees Ferry flow yields an average rate of 10 maf for the next 25 years. As drought conditions further intensify due to heat, Colorado River flows would decline further (see charts below), averaging 7 maf during 2035-2060, values equivalent to the observed lowest flow at our recent drought's nadir.

Are such low flows realistic on a year-by-year sustained level? First, virtually all simulations point to sufficient drought to reduce flow below current consumptive uses on the river within 20 years, although the range of model outcomes indicates that we don't know precisely how low the flow will be. Second, whereas the 21st century climate change signal is one of low Colorado River flow, the superimposed natural variability in precipitation is still capable of producing "normal" flow (by 20th century standards) for a year or two within an otherwise drought epoch. Finally, it is unclear whether the historical Lees Ferry flow-PDSI relation used in this study is strictly applicable to the substantial change in climate that is projected.

Nonetheless, a robust physical relation underpins the projected reduction in Colorado River flow. Evapotranspiration exceeds precipitation throughout the basin, implying less runoff as dictated by water balance requirements. Also, the Lees Ferry flow estimated from the climate simulations for 1990-2005 is 13 maf, an already substantial decline from higher simulated flows in the early 20th century. This change is remarkably consistent with observations and suggests an emerging warming effect on streamflow.

Relative to the 1990-2005 mean flow of 13 maf, the 42-run average predicts a 25 percent decline in streamflow during 2006-2030, and a 45 percent decline during 2035-2060. This scenario is consistent with several independent estimates using different approaches. Revelle and Waggoner (1983) used empirical methods to predict a 29 percent reduction in Lees Ferry flow under a scenario of 2°C warming. Christensen and others (2004) used a sophisticated hydrology model to predict an 18 percent reduction in Colorado River streamflow by 2050 under a change scenario derived from a climate model that is now recognized to be on the low range of climate change sensitivity. Milly and others (2005) diagnosed annual runoff in 12 different AR4 models and discovered a near 20 percent decline in runoff for the Colorado River headwaters by 2050.

Our study reveals that a sustained change in moisture conditions is unfolding within the broad range of natural variations. The Southwest is likely past the peak water experienced in the 20th century preceding the signing of the 1922 Colorado Compact: a decline in Lees Ferry flow will reduce water availability below current consumptive demands within a mere 20 years. These projections further expose the risky reliance by Colorado River water users upon the Compact as a guarantee that streamflows will always materialize to match legislated requirements.

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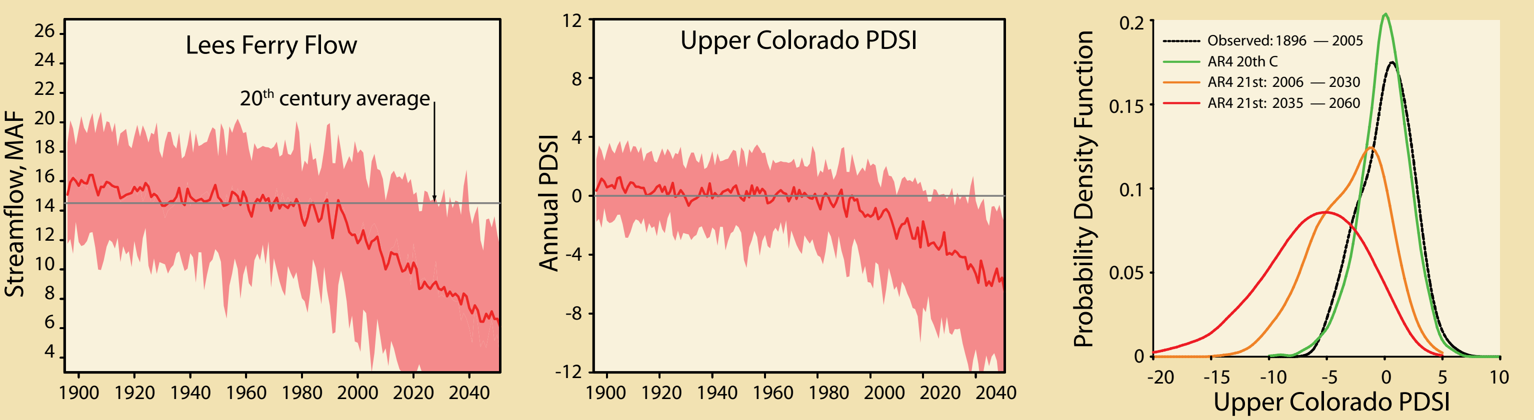

The 1895-2050 Lees Ferry annual streamflow (left) was derived from the AR4 simulations of PDSI (middle) using the downscaling formula that relates observed Lees Ferry flow to observed PDSI during the 20th century. The dark red curve denotes the 42-run average, and the cloud describes the 10 to 90 percent range of individual simulations. The right panel summarizes the probability distribution function of PDSI averaged over the Upper Colorado Drainage Basin for individual years of observations 1895-2005 (black), for the 42 models for 1895-2005 (green), and for the 42-model projections of the average PDSI during 2006-2030 (orange) and 2035-2060 (red). Note that the models produce a realistic range of PDSI drought events during the 20th century, and for the future they produce surface moisture conditions that denote progressive aridification and severe drought conditions.