Trends in the hydrology of the western US bear the imprint of manmade climate change

Water managers may no longer be safe in assuming that resources will remain within their historical range of uncertainty.

The snowpack in the western US has been declining over the past 50 years—a trend that should alarm urban dwellers of Los Angeles as much as skiers in Park City, Utah. Furthermore, the snow runoff has been occurring earlier in the year, so that less water flows through rivers during the later months of the summer. The decreasing river flow further stresses a region that is experiencing drier summer conditions. In the past few years, large and intense fires have ravaged western forests, and water levels in the region's critical reservoirs have dropped to alarmingly low levels. Lake Mead in Arizona and Nevada, a lifeblood of cities and farms in the Southwest, is currently only half full, as seen in figure 1.

Figure 1. Lake Mead's water level has fallen dramatically in recent years, as seen by the exposure of formerly submerged white rock. Located in Nevada and Arizona, this reservoir on the Colorado River is currently only half full. (Photo courtesy of Ken Dewey, University of Nebraska, Lincoln.)

The West has, of course, experienced—and survived—such dry spells before. The current one may be no more than a pendulum swing of the natural climate cycle. Still, hydrologists can't help suspecting that manmade additions of greenhouse gases and aerosols to the atmosphere are affecting the regional climate system. Scientists who participated in the most recent report of the Intergovernmental Panel on Climate Change have deduced that greenhouse-gas emissions account for most of the planet's recent warming on a global scale.[1] It's much harder, however, to detect the impact of those human-induced changes on a specific region.

Nevertheless, Tim Barnett of the Scripps Institution of Oceanography and a team of other climate scientists set out to do just that. Team members hail from Scripps, Lawrence Livermore National Laboratory, the University of Washington, and the National Institute for Environmental Studies in Tsukuba, Japan. They compared the predictions of computer climate models to the measurements of three temperature-sensitive hydrological variables in many different regions of the western US.[2] Only by including greenhouse gases and aerosols in the model simulations could they adequately reproduce the spatial and temporal pattern of the changes that have been observed over the past 50 years. They concluded that up to 60% of the trends in river flow, in minimum winter air temperature, and in spring snowpack over the past half century are human induced.

Earlier studies with computer climate models had predicted that manmade climate change would bring a more arid climate to the southwestern US.[3] The paper by Barnett's team goes further by attributing the observed changes to global warming, comments Ronald Stouffer of the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL). The new study, he notes, finds that not only warmer temperatures but also temperature-related hydrological parameters are consistent with the human fingerprint.

Julio Betancourt of the US Geological Survey in Tucson, Arizona, added that people studying the time series of many climate-related variables had been noticing a rather sudden change, an inflection point, around the mid-1980s.[4] "They wondered whether the change was due to natural variability or to the greenhouse-gas impact," said Betancourt. "The jury was out until the Barnett group's paper came along."

Detection and attribution

Barnett and coworkers focused on three parameters that are expected to be affected by changing temperatures. One was *SWE*/*P*, or the amount of snow in the mountains on 1 April, measured as the snow–water equivalent *SWE*, normalized by the total precipitation *P* during the months of October through March. The normalization ensures that the numbers are not skewed by dry or wet winters. A second parameter was the daily minimum temperature averaged over the months of January through March ($JFM\ T_{min}$). The third parameter was the center of timing (*CT*) of river flow—that is, the day of the year when half the total annual water flow has occurred in a stream gage in a given river.

Barnett's team studied the measured values of *SWE*/*P* and $JFM\ T_{min}$ in each of nine western regions in the years from 1950 to 1999 as well as determinations of *CT* over the same time period for three major river drainage systems: the Columbia River, the Colorado River, and the Sacramento and San Joaquin rivers. As illustrated in figure 2, the data in different regions, while showing considerable natural variation, all manifested similar trends. (The top two panels of the figure show only three of the nine regions.) All regions but one had retained less winter precipitation in the spring snowpack. The winters were getting warmer in all regions, and the river runoff was occurring earlier.

To compare the observations with what might be expected in a green-

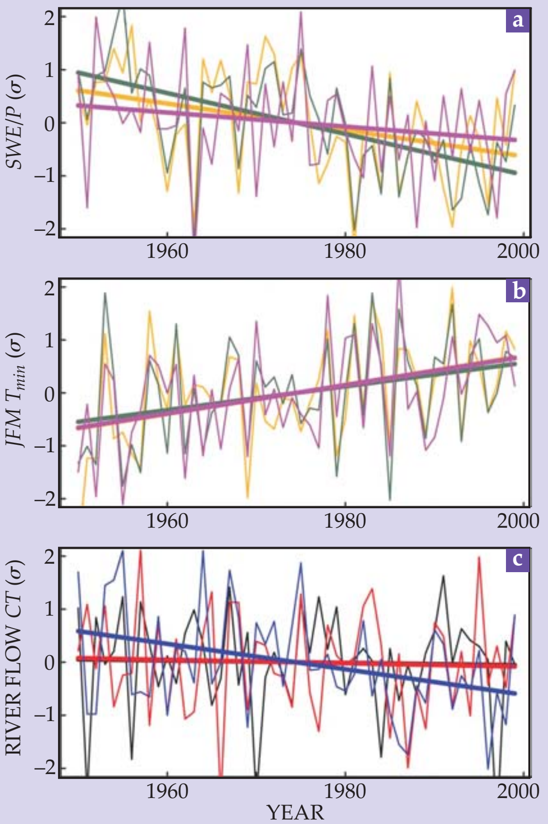

Figure 2. Trends in hydrology of the western US. **(a)** Time series of the normalized snow–water equivalent (*SWE*/*P*), the fraction of precipitation remaining as spring snow, at three different mountain ranges: the Cascades in Washington state (yellow), the northern Rockies (green), and the northern Sierras (purple). **(b)** Time variation in the minimum January–March temperature (*JFM* T_{min}), in the same three mountain ranges. **(c)** Center of timing (*CT*) for the river flow in the Sacramento and San Joaquin rivers (black), the Colorado (red), and the Columbia (blue). Each plot shows the deviation of the measurement from the long-term average, expressed as a multiple of one standard deviation. Despite the considerable fluctuations, the data follow similar trends. In panel b, the purple line hides the yellow line, and in panel c, the red line hides the black one. (Adapted from ref. 2.)

house-gas-warmed world, the researchers started with a global climate model. Such models predict the temperatures and precipitation levels that result with and without the global input of greenhouse gases and aerosols. The researchers chose two particular models that were known to give a realistic climate and level of natural variability, especially in the western US, their area of interest. They took the temperature and precipitation predicted by those models, downscaled them to a finer grid in the region of interest, and used them as input to a regional hydrological model. The hydrological model then produced estimates of *SWE*/*P*, *JFM* T_{min}, and river *CT* to compare with the observations.

The spatial and temporal patterns of changes in the hydrological parameters predicted by models that include greenhouse gases and aerosols make up a "fingerprint" of climate change induced by human activity. That fingerprint was compared mathematically with the pattern of observed change. The comparison involves computing the correlation between the observed and model predicted fingerprints. Statistical tests showed the two fingerprints to be indistinguishable from each other over the 50-year span of the study. Moreover, climate models run with only internal climate physics—that is, with no greenhouse gases or aerosols—could not explain either the human-induced fingerprint or that obtained from observation. In short, natural climate change was not responsible for the observed changes. The same held true with fingerprints from climate models that included observed changes in solar and volcanic forcing. The researchers thus concluded that the climate changes observed in western hydrology over the past 50 years are largely caused by human impact.

Water management

Attributing the hydrological changes to human-induced changes in climate has important implications for water management. The job of water managers is to plan for changes in a watershed and adjust their practices accordingly. The normal assumption is that levels of water in a river, for example, will fall and rise as droughts come and go but the system will fluctuate within some envelope of natural variability well established by its past behavior. If, however, the system is now feeling the impact of human-induced changes, historic behavior can no longer be a guide.

A warning along those lines was recently issued by Christopher Milly of the US Geological Survey (USGS) along with six other water and climate scientists.[5] They point to the predictions of climate change worldwide, which strongly suggest that water management can no longer be business as usual. The authors assert that predicted changes in runoff now are large enough to push hydroclimate beyond the range of historical behaviors. Milly and his colleagues call for greater interaction between water managers and the scientific community so that the scientists can help develop statistical tools to cope with the changing conditions.

Barnett and his Scripps colleague David Pierce have looked at a specific water management challenge: the dwindling supply of Colorado River water and the increasing demands being made on it.[6]

The allocation of water from Lake Mead and its newer upstream cousin, Lake Powell, has been governed by the Colorado River Compact of 1922 (see cover). Thanks to tree-ring reconstructions of the streamflow over the past 500 years,[7] we now know that the Colorado River in 1922 was experiencing relatively high annual flows. The compact promises 7.5 million acre-feet per year, or fully half of the current annual flow of 15 maf, to Nevada, Arizona, and California. (An acre-foot is roughly the average annual water use of a typical US family household.) All scheduled depletions for 2008 total 13.5 maf/yr. Those depletions do not include losses due to evaporation and exchange with the surrounding ground, which are currently about 1.7 maf/yr.

Barnett and Pierce point out that this level of depletion is not sustainable, especially if one folds in the predictions of global climate models that river runoff in the region will fall by 10%–30% by 2050. Barnett acknowledges that global models don't agree well with each other when it comes to predicting precipitation, but one of the two regions of the world where the models do agree—and where they all predict a drying—is in the southwestern US.

Assuming the drop in river runoff predicted by climate models, Barnett and Pierce do a simple water budget to project how long Lake Mead can continue to meet its obligations. They conclude that the reservoir has a 50% chance of going dry by 2021 if no changes are made in its water allocation.

Gregory McCabe and David Wolock

of the USGS have studied the impact of warmer temperatures on river flow in the Colorado River basin, folding in the variability seen in the tree-ring records; they also warn of potential water shortages there.[8] The National Research Council released a report last year dealing with the need to adjust Colorado River basin water management to the changing hydrological conditions.[9]

The development of the West depended on the availability of water. Its survival will depend on the wise management of that critical resource.

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Light exhibits a spin Hall effect

Whenever a linearly polarized beam of light refracts, it splits into two parallel, almost overlapping beams of opposite circular polarization.

Applying an electric field along a frigid strip of near-defect-free semiconductor can drive a lateral imbalance of spin-up and spin-down electrons, a spin Hall effect. The effect, which comes in several varieties, depends at heart on the coupling between the electrons' spin and orbital angular momentum (see PHYSICS TODAY, February 2005, page 17 and January 2008, page 19).

Light can have both spin—in the form of circular polarization—and orbital angular momentum or helixity. Could coupling between the two momenta engender a spin Hall effect for light? As Onur Hosten of the University of Illinois at Urbana-Champaign and his thesis adviser Paul Kwiat demonstrate in a new experiment, the answer is yes.[1]

In the Illinois experiment, the role of the electric field was played by a stepwise gradient in refractive index. The role of spin-up and spin-down electrons was played by light's right-hand and left-hand components of circular polarization. The effect itself appeared as a tiny lateral separation of the two circularly polarized components as they passed at an angle from air into glass.

Kwiat's lab specializes in quantum information. Although his and Hosten's experiment can be understood in terms of the equations devised in the 19th century by Augustin-Jean Fresnel and James Clerk Maxwell, the Illinois researchers chose instead to analyze their experiment in the quantum framework of spin–orbit coupling.

A quantum treatment could help identify quantum applications, Kwiat says. Moreover, to amplify the tiny separation enough to see it, he and Hosten exploited an esoteric quantum technique called weak measurement.

Theory first

That light could exhibit a spin Hall effect emerged from theoretical attempts to account for an effect predicted in 1955 by Fedor Fedorov[2] and measured in 1972 by Christian Imbert[3]: When a beam of circularly polarized light undergoes total internal reflection, the beam shifts transverse to the direction of propagation.

In 2004 Masaru Onoda of Japan's National Institute of Advanced Industrial Science and Technology in Tsukuba and Shuichi Murakami and Naoto Nagaosa of Tokyo University saw in the Imbert–Fedorov effect a resemblance to the spin Hall effect, which Murakami and Nagaosa both study.

To emphasize the resemblance, Onoda, Murakami, and Nagaosa analyzed the case of photon wavepackets propagating in a photonic crystal whose refractive index varies periodically.[4] They predicted that the circularly polarized components of a linearly polarized beam would separate from each other by a distance of about 100 times the crystal's lattice constant.

In principle, that separation, being