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# Stationarity Is Dead

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Times have changed. I "pen this note" on the keyboard of my portable computer. I'm working from home today, but my home and are in some senses indistinguishable these days, thanks (if that's the right word) to technology.

On this particular day, the fusion of home and office is a convenience. New Jersey is in a state of emergency. Outside, the winds are howling on the tail end of a rain-plus-sleet-and-snow Nor'easter that has closed schools, businesses, government offices, and roadways. Between the howls, I hear the comings and goings of the sirens of emergency vehicles.

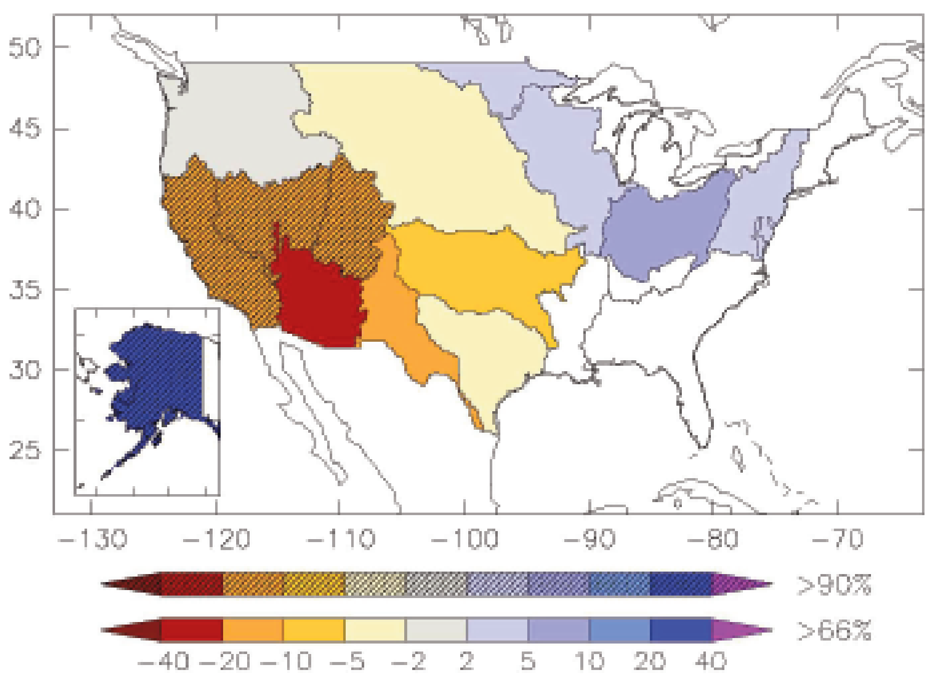
No doubt some people will attribute this April storm to climate change. I could sneer that a single realization of a random process is not a terribly robust indicator of a shift of a probability density function. But I will not, because I know that such "popular attributions" are based not only on the event in question, but also on experiences and information accumulated over recent years. And that information includes reports from the climate-science community (www.ipcc.ch).

I would argue, in fact, that changing climate is the new "default hypothesis," rapidly displacing the assumption of stationarity upon which generations of hydrologists and engineers have built their careers—not to mention untold dollars worth of dams, wells, levees, reservoirs, hydroelectric power plants, bridges, irrigation systems, and culverts.

Stationarity is the assumption that the future will be similar to the past, in a statistical sense. Historical observations have been the raw materials for hydrologic analyses under the fast-fading regime of stationarity. If we can no longer invoke stationarity to convert observations into predictions, what can we do? What additional ingredients are needed for hydrologic analysis?

Numerical models of climate dynamics provide one of the ingredients that will inform hydrologic analyses of the future. Such models can already suggest the directions and rates of change of hydrologic processes, and this may be enough information to suggest appropriate responses to the most urgent risks. In the future, the models will hopefully become increasingly accurate and precise, and the use of their output seems likely to become increasingly routine.

When discussing application of climate models to hydrology, it is best to be candid about the difficulties. Climate models were not built to support hydrologic analysis. Their representation of continental water fluxes is crude. Processes are described on horizontal length scales (hundreds of kilometers) that one is tempted to dismiss as laughably inadequate. But such scales are sufficient to define major shifts in climate, and climate is a major determinant of water availability.




Model-Projected Changes in Annual Runoff from U.S. Water Resource Regions, 2041-2060. Percentage change relative to 1900-1970 baseline. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement. After Milly, P.C.D., K.A. Dunne, A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438: 347-350.

What do climate models tell us about the decades ahead? The accompanying figure indicates that the American Southwest will produce less runoff during the 21st century than it did during the 20th century. When interpreting the meaning of "runoff" from a climate model, we should think not only of surface runoff, but also of recharge to, and eventual discharge from, ground water systems, though these are not explicitly represented in the models. Discharge response is eventual because ground water response times, especially in arid environments, can be long relative to the time scale of anthropogenic climatic change.

The prospective reductions in ground water recharge in the Southwest are accompanied by projected reductions in surface runoff. Climate models do not currently include water use, but it can reasonably be hypothesized that water demands for agriculture and domestic use, other things being equal, will increase in those regions where climate warms and dries. With decreasing surface runoff and increasing water demand, the development of ground water sources, within the context of deliberate conjunctive use, probably cannot be taken off the table categorically as an option, even where a general decrease in recharge is projected. However, there is no escape from the law of conservation of mass.

This discussion is presented only at the crudest scale. In the West, for example, climate change does not simply rescale the size of all water fluxes equally in space and time. Rising temperatures change the partitioning of precipitation between snow and rainfall, and this change cascades through the system, as noted in an accompanying article in this issue by Mike Dettinger and Sam Earman.

As the climate warms, mountain glaciers melt. The liquid remains of their existence flow to the sea. Meanwhile, ocean water

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warms and expands. As a result of these two processes (and ignoring speculation about potential for rapid losses from the Greenland and Antarctic ice sheets by unmodeled processes), sea level is expected to rise slowly but relentlessly for the next several centuries. Climate models project a rise (central estimate) of a bit more than a foot during the 21st century. Impacts on coastal water supplies have not been evaluated quantitatively, but could be expected to include increased salinity from subsurface and surface saltwater intrusion and from increasing frequency of surface inundation of land.

Stationarity is dead. Times have changed, and the change is ongoing. The full extent and nature of the change are uncertain. The impacts are even foggier. In view of this, what are the appropriate adaptations to address those impacts? Addressing this question will be a major challenge for water science during the 21st century.