CLIMATOLOGY

Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest

Toby R. Ault,[1]* Justin S. Mankin,[2,3] Benjamin I. Cook,[2,3] Jason E. Smerdon[2]

Megadroughts are comparable in severity to the worst droughts of the 20th century but are of much longer duration. A megadrought in the American Southwest would impose unprecedented stress on the limited water resources of the area, making it critical to evaluate future risks not only under different climate change mitigation scenarios but also for different aspects of regional hydroclimate. We find that changes in the mean hydroclimate state, rather than its variability, determine megadrought risk in the American Southwest. Estimates of megadrought probabilities based on precipitation alone tend to underestimate risk. Furthermore, business-as-usual emissions of greenhouse gases will drive regional warming and drying, regardless of large precipitation uncertainties. We find that regional temperature increases alone push megadrought risk above 70, 90, or 99% by the end of the century, even if precipitation increases moderately, does not change, or decreases, respectively. Although each possibility is supported by some climate model simulations, the latter is the most common outcome for the American Southwest in Coupled Model Intercomparison 5 generation models. An aggressive reduction in global greenhouse gas emissions cuts megadrought risks nearly in half.

INTRODUCTION

Megadroughts are periods of aridity as severe as the worst multiyear droughts of the 20th century and persist for decades. These droughts are known to have occurred in the American Southwest (*1*, *2*) and other parts of the world (*3*, *4*) during the past millennium, and they have been linked to the demise of several preindustrial civilizations (*3*, *5*, *6*). A megadrought occurring again in the Southwest in the coming decades would impose unprecedented stresses on water resources of the region, and recent studies have shown that they are far more likely to occur this century because of climate change compared to past centuries (*7*, *8*).

Estimating the probability of a megadrought under different climate change scenarios is critical for effectively evaluating risk and managing water resources, but recent studies have disagreed on the relative odds of these events. For example, on the basis of precipitation projections and paleoclimate data, Ault *et al.* (*8*) argued that the risk of multidecadal megadrought in the American Southwest would increase at least twofold from 5 to 15% over the last millennium to between 20 and 50% this century; Cook *et al.* (*7*) estimated those risks to be much higher in an analysis of a wider range of soil moisture indicators of varying levels of complexity. Further complicating this picture is that certain regions (for example, much of the American West) are expected to become drier, on average, even with a predicted increase in precipitation because of the increased demand for moisture by the atmosphere and consequent increases in evapotranspiration (*9*, *10*). It is therefore critical to clarify the relative contributions of precipitation and temperature to future megadrought risk.

Here, we focus on characterizing megadrought risk as a function of variables that govern the balance of moisture at the land surface during climate change. At decadal and longer time scales, these variables are primarily precipitation, which supplies moisture, and temperature and vegetation, which modulate evapotranspiration (*9*, *11*). Although climate change projections of higher temperatures are robust and broadly consistent across different model simulations, projections of precipitation change are subject to considerably more uncertainty. Moreover, megadroughts are extreme events that unfold over decades, implying that even state-of-the-art multimodel ensembles used for the Intergovernmental Panel on Climate Change (IPCC) will have only a handful of realizations of these intervals at best. This small sample size inherently makes estimating the probability of a megadrought challenging because any empirical probability density function (PDF) of its occurrence will be finite and incomplete. For example, imagine two simulations run with a model that predicts overall drying: In the first realization, there is a megadrought, and in the second, there is none. The model-predicted probability would appear to be 50% regardless of the true megadrought PDF. As an alternative, we characterize the megadrought PDF by asking the following: (i) What are the changes in regional hydroclimate that elevate (or lower) megadrought risk? (ii) How do state-of-the-art general circulation models (GCMs) simulate the variables that govern megadrought risk?

We adopt a probabilistic framework for quantifying the risk of future events under a broad range of possible climate outcomes and then compare GCMs against these possibilities. Although there are a number of objective methods for identifying periods of megadrought in a hydroclimate time series (*12*–*16*), here we define a megadrought as a multidecadal (35-year) period of aridity as bad as, if not worse than, the worst droughts of the 20th century (−0.5 of an SD on average; Materials and Methods). By megadrought "risk," we refer to the probability of an event occurring this century, acknowledging that the statistics of regional hydroclimate in the future will likely be different from past statistics. This notion of risk accommodates the possibility that an event might not unfold even if megadroughts are generally more likely to occur (for example, a few fortuitous wet years in a drier climate with higher megadrought risk could prevent an event from fully unfolding).

Quantifying megadrought risk over a wide range of plausible climate change outcomes allows us to assess how deterministic GCMs, forced with rising greenhouse gas (GHG) concentrations, simulate changes in temperature and precipitation associated with different levels of risk

[1]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853, USA. [2]Division of Ocean and Climate Physics, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA. [3]NASA Goddard Institute for Space Studies, New York, NY 10025, USA.
*Corresponding author. Email: toby.ault@cornell.edu