Exploring Drought and Its Implications for the Future

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Worsening drought, water restrictions, and wildfires have been widely featured in news reports across North America during recent years. Area burned by wildfire was at unprecedented levels in the United States in the summer of 2002, and devastating wildfires in California were in the news just a few months ago. Drought is not only gripping parts of North America, but also parts of Northern Africa and other regions worldwide, serving as a reminder of society's vulnerability to drought and its enormous economic impact.

But what is the full range of past drought variability, as revealed by paleoclimate data? What role might droughts associated with abrupt climate change play? Are droughts likely to become more frequent, longer, or more extensive as we move into the future with global warming?

All of these considerations were motivation for organizing a meeting, "A Multi-millennia Perspective on Drought and Implications for the Future." It was arranged by the international CLIVAR-PAGES joint working group, which brings together the climate dynamics and paleo-communities, and fosters interactions that have been exceedingly fruitful. (CLIVAR is the World Climate Research Program's project on Climate Variability and Predictability, and PAGES is the International Geosphere Biosphere's project on Past Global Changes.) Drought is among the topics of the Intergovernmental Panel on Climate Change (IPCC) for the forthcoming 2007 fourth assessment report (AR4), and co-sponsorship of the meeting by the IPCC enabled attendance by scientists from developing countries in Africa and elsewhere.

The purpose of the meeting, which was attended by about 70 people, was to bring a focus on new ideas, observations, analyses, and theories about drought to improve understanding, analysis approaches, and predictive capabilities. The main focus regionally was on North America and Northern Africa, the two regions with the largest amount of available, drought-related paleo-data and research, as well as serious ongoing droughts.

Meteorological drought is defined in terms of a deficit of precipitation. Agricultural drought relates mostly to deficiency of soil moisture, while hydrological drought relates to deficiencies in lake levels and streamflow. The characteristics of precipitation of frequency of occurrence, sequence, intensity, and phase (snow versus rain), in addition to amount, are important. Regular light or moderate rains soak into soils and benefit agriculture, but may not run off to produce streamflow; while occasional, intense rains may cause local flooding and runoff into streams, but may not replenish soil moisture enough to last until the next event. Drought and flood are extremes of the frequency, intensity, and amounts of precipitation characteristics [*Trenberth et al.*, 2003].

Observational Studies of Drought

The greatest severity and extent of drought in the United States occurred during the Dust Bowl years of the 1930s, particularly during

1934 and 1936. The decades of the 1950s and 1960s were also characterized by episodes of widespread, severe drought, while the 1970s and 1980s as a whole were unusually wet. However, drought conditions that began in the west in 1998 have persisted in many areas through the summer of 2003. Often, a very few storms or precipitation events are responsible for the difference between dry versus wet years. Dry years tend to be clustered more than wet years.

Globally, drought areas increased more than 50% during the 20th century, largely due to the drought conditions over the Sahel and Southern Africa during the latter part of the century, while changes in wet areas were relatively small. The Palmer Drought Severity Index (PDSI) from 1870 to 2002 shows the dominance of precipitation variations in its spatial and temporal variability. The biggest source of drought worldwide is El Niño Southern Oscillation (ENSO), which also highlights the concurrent nature of floods and droughts, with droughts favored in some areas during El Niño, while wet areas are favored in other areas. These tend to switch during La Niña in the tropics and subtropics (see *Cole et al.* [2002] for effects on the United States).

Paleo studies show dramatic observed changes in drought and the hydrological cycle over many parts of the world. A growing wealth of paleo-data reveals that decades-long droughts (sometimes termed "mega-droughts"), such as the current Sahel drought, are not uncommon [e.g., *Verschuren et al.*, 2000]. Moreover, this scale of drought has been eclipsed in the past by droughts lasting a century or more [e.g., *Laird et al.*, 1996]. Thus, the full range of drought variability is potentially much larger than has been seen in the last 100 years.

For example, in North America, Dust Bowl-length events occurred on average one to two times per century, and longer, 10–25-year events occurred as well [*Woodhouse and Overpeck*, 1998]. A drought lasting over 20 years across much of the conterminous United States occurred in the late 16th century, and it appears that droughts in the Sierra Nevada region have lasted over 100 years in the past [e.g., *Stine*, 1994]. Although the most detailed reconstructions of past North American drought have been realized through analysis of tree rings, strong supporting evidence is provided by limnological indicators on lake levels and aeolian sand deposits that indicate dune reactivation. Luminescence dating techniques that do not depend on the presence of organic matter provide new insights into the latter.

Mega-droughts in the past have had major impacts on civilizations. Convincing evidence from closed basin lakes in the Yucatan peninsula of Mexico suggests that a series of three droughts around 810, 860, and 910 A.D. coincided with the collapse of the Mayan civilization [*Haug et al.*, 2003].

Modeling Processes Involved in Drought

Several long coupled model runs with unchanging external forcing of the climate have been analyzed in preliminary ways for natural incidence of drought. Furthermore, paleo-model results for Africa 8500 B. P. in the National Center for Atmospheric Research Community Climate System Model reveal that the large changes in the orbit of the Earth around the Sun increase insolation in the boreal summer, enhance land-sea contrast, and drive a stronger and 7° latitude farther northward ITCZ (Inter-Tropical Convergence Zone) over Africa, making for a much wetter Sahel and a smaller Sahara desert.

A long-standing concern has been the possibility of increased drought in the future, as the climate changes with increased greenhouse gases in the atmosphere. Increased heating ("global warming") produces increased drying and hence evaporation if moisture is available [*Trenberth et al.*, 2003]. Because evaporation generally exceeds precipitation across the United States in the deep summer months of July and August, a primary risk is of increased summer continental drought. Drier soils and less recycled moisture in the atmosphere is a recipe for increased intensity, frequency, and duration of drought. These general mechanisms were found to occur in the new version of the Geophysical Fluid Dynamics Laboratory model.

But are there other physical processes that could operate in specific regions? Observed major droughts wax and wane in extent and duration, often in an apparently random manner. The meeting highlighted some underlying patterns and their causes. Generally, changes in global sea surface temperatures (SSTs) that are most pronounced during El Niño events result in weather patterns that selectively favor drier regions in some locations, and wetter regions elsewhere, as storm tracks and anticyclones shift. Changes in the land surface—whether caused by humans or by the changing climate—can produce amplifying effects, especially in summer. In models, soil moisture is an important feedback, but most models do not allow vegetation and ecosystems to evolve other than as specified by season. As a result, the full response to climate variations and change is not apt to be simulated, although work is progressing on developing dynamic vegetation models.

Meeting presentations illustrated how several improved climate models now suggest that major droughts, such as those during the Dust Bowl and in the Sahel, can be simulated in atmospheric models by specifying the SSTs, suggesting that they may have some predictability [e.g., *Giannini et al.*, 2003]. These studies also indicate that changes in vegetation and land use are much less likely to be a fundamental cause of droughts in these two cases, but rather, represent strong feedbacks that may extend the duration of drought.

Key areas of SST change include the warming of the tropical Indian Ocean, the cold phase of the Pacific Decadal Oscillation (PDO), inter-hemispheric SST differences, and Atlantic SSTs. As some changes in SSTs in recent decades are linked to global warming and human influences, are particular regions already at an increased risk of droughts due to human activities?

Wide-ranging discussions at the meeting also focused on definitions of drought, how good the observational record is and how to improve it, the role of external forcings (such as the Sun and volcanoes), internal forcings (such as SSTs and land surface properties) and human influences, and linearity of records. The paleo-record discussion centered on replication of records, the spatial distribution of sites, improving chronologies and temporal resolution, data limitations, uncertainty and errors affecting the validity of paleoclimate data, implicit time-averaging of coarse-resolution paleo-records, calibration and verification issues, difficulties with interpretation of isotopic indicators, and whether it is possible to get at intensity, frequency, amount of precipitation, as well as phase.

It was noted that the direct relevance of the glacial-era record to abrupt climate change is hard to defend, as conditions today and in the future are or will be very different. Examples of recent, relevant, abrupt change in the instrumental record include the 1960s Sahel drying and the 1976 climate shift in the Pacific and ENSO. More significant abrupt shifts in North American and North African hydrologic regimes occurred in the past as well. The feedback from vegetation changes, which was highlighted in the meeting, may be among the non-linear factors involved in abrupt change [see also *Alley et al.*, 2003]. It is expected that unanticipated drought will be a feature of climate in the near future, particularly given continued global warming.

For complete background materials, venue, agenda, speakers, and participants, see Web site: http://ipcc-wg1.ucar.edu/meeting/wg1/Drght.

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References

Alley, R. B., et al., Abrupt climate change, *Science, 299*, 2005-2010, 2003.

Cole, J. E., J. T. Overpeck, and E. R. Cook, Multiyear La Niña events and persistent drought in the contiguous United States, *Geophys. Res. Lett., 29*, doi: 10.1029/2001GL013561, 2002.

Giannini, A., R. Saravanan, and P. Chang, Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales, *Science, 302*, 1027–1030, 2003.

Haug, G. H., D. Gunther, L. C. Peterson, D. M. Sigman, K. A. Hughen, and B. Aeschlimann, Climate and the collapse of the Maya civilization, *Science, 299*, 1731–1735, 2003.

Laird, K. R., S. C. Fritz, K. A. Maasch, and B. F. Cumming, Greater drought intensity and frequency before A.D. 1200 in the northern High Plains, U.S.A., *Nature, 384*, 552–554, 1996.

Stine, S., Extreme and persistent drought in California and Patagonia during mediaeval time, *Nature, 369*, 546–549, 1994.

Trenberth, K. E., A. Dai, R. M. Rasmussen, and D. B. Parsons, The changing character of precipitation, *Bull. Am. Meteorol. Soc., 84*, 1205–1217, 2003.

Verschuren, D., K. R. Laird, and B. F. Cumming, Rainfall and drought in equatorial east Africa during the past 1,100 years, *Nature, 403*, 410–414, 2000.
Woodhouse, C. A., and J. T. Overpeck, 2000 years of drought variability in the central United States, *Bull. Am. Meteorol. Soc., 79*, 2693–2714, 1998.

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