CLIVAR/PAGES/IPCC Workshop

"A multi-millennia perspective on drought and implications for the future"

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Tucson, AZ

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

also: Trenberth, K., J. Overpeck and S. Solomon, 2004: Exploring drought and its implications for the future. *Eos,* 85, No. 3, 20 Jan. 2004, p27.

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1. Organizational Acronyms Used

CLIVAR is the WCRP program on Climate Variability and Predictability
IGBP is the International Geosphere Biosphere Program
IPCC is the Intergovernmental Panel on Climate Change
NCAR is the National Center for Atmospheric Research
NCDC is the National Climatic Data Center
NOAA is the National Oceanographic and Atmospheric Administration
NSF is the US National Science Foundation
PAGES is the IGBP program on Past Global Changes
WCRP is the World Climate Research Program

2. Introduction

Worsening drought, water restrictions and wildfires have been widely featured in news reports across North America during recent years. Devastating drought is still gripping parts of Northern Africa as well as other regions. More and more, these serve as a reminder of the vulnerability of society worldwide to drought. As an example, drought conditions continue to be widespread across the western parts of the United States (Figure 1) and parts of Mexico. Snow pack in the Rocky Mountains has been at chronically low levels in many places for several years. Wildfire area-burned numbers were at unprecedented levels in the 2002 summer. Devastating wildfires were in the news in October in California and Colorado, well after the summer season. Drought has enormous economic impact, for instance it was reported that the 1988 summer drought in the United States cost $40 billion. In that case it was a short event, but impacts and costs can be much greater if there are longer or recurring droughts, such as occurred in "Dust Bowl" period in the 1930s.

There is considerable evidence for drought from the instrumental record over the past century or so, but what is the full range of past drought variability? As we look to the future it is worthwhile trying to place the relatively short instrumental period of the last hundred years or so in historical context. A better perspective can be gleaned from the paleoclimate record using indicators of past climate that are sensitive to hydrologic conditions, such as of tree rings and sediment proxies. Further, given advent of drought, what are the causes and can drought be predicted? Or is it an unpredictable part of natural variability? What have been the manifestations of drought and what are the possible lessons for the future?

Paleoclimate records suggest that abrupt climate change has been very important during or emerging from glacial periods. The main hypotheses relate to the role of ice: melting ice freshens the ocean, alters ocean currents and can change the thermohaline circulation (e.g., the Younger Dryas period about 11,000 years ago). The changes are large at high latitudes and temperature is a key variable. However, as we move into the future with global warming, it appears that ice will not be as large a factor. Nevertheless, we hypothesize that abrupt climate change is also possible and even likely in warm climates but may be manifested through changes in precipitation regimes and drought. Is this so? Such changes can greatly impact the environment and societies.

All of these considerations were motivation to organize a workshop focused on "A multi-millennia perspective on drought and implications for the future". The workshop was initially organized as one in a series under the auspices of the international CLIVAR-PAGES joint working group. CLIVAR is the World Climate Research Program's project on Climate Variability and Predictability, and PAGES is the International Geosphere Biosphere Program's project on Past Global Changes. These workshops have therefore brought together the climate dynamics and the paleoclimate communities and fostered interactions that have been exceedingly fruitful. In addition, future drought is a major concern of the Intergovernmental Panel on Climate Change (IPCC), and IPCC decided to also co-sponsor the workshop. Primary funding for the workshop came from NOAA and NSF. The IPCC supported the involvement of scientists from developing countries.

The purpose of the workshop, held in Tucson, Arizona, 18-21 November 2003, was to bring a focus on new ideas, observations, analyses and theories about drought to highlight ways of improving understanding, analysis approaches, and predictive capabilities. The main focus regionally was on North America and Northern Africa. These are the two regions with the largest amount of drought-related paleo-data and research, as well as serious current droughts. Special attention was given to the historical context and the paleoclimatic record. Papers were presented dealing with all facets of the topics discussed above. Working groups summarized findings and made recommendations for future research and activities.

3. Initial Plenary Talks and Discussion

3.1. Opening session

While there was some discussion about definitions of drought, there was also recognition that the definition appropriately varies depending on circumstances. *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. In the opening talk, K. Trenberth highlighted the importance of the characteristics of precipitation: frequency of occurrence, sequence, intensity, and phase (snow versus rain) in addition to amount. Regular light or moderate rains soak into soils and benefit agriculture, but may not runoff to produce streamflow, whereas occasional intense rains may cause local flooding and runoff into streams, but may not replenish soil moisture enough to last until the next event. Trenberth provided a conceptual framework for why it rains, or why it does not, and noted that drought and flood are extremes of the frequency, intensity and amounts of precipitation characteristics. He illustrated the concepts with recent observed events, such as the 2002 floods in Europe and the 2002 drought in the western U.S. and noted the role of changes in sea surface temperatures (SSTs) and El Niño in particular. Trenberth went on to consider how precipitation should change as the climate changes, especially as we move into the future (discussed below).

In highlighting the PAGES concerns about drought, J. Overpeck focused on the full range of past drought variability, and in particular mega-droughts in many parts of the world, especially Africa and North America. "The more we look, the more we find mega-drought". He emphasized the importance of apparent hydrologic regime shifts that are manifestations of local abrupt climate change and he challenged the audience to say more about possible forcings, such as the role of solar variability, and our ability to model such events. He further noted the need for more paleoclimatic data and the requirements for data management. Specifically, more work on interdisciplinary metadata is needed along with better access to the data.

The IPCC perspective on the workshop was introduced by S. Solomon, co-chair of WG1 of IPCC. She outlined the framework for the forthcoming 2007 fourth assessment report (AR4) and highlighted the need to place the instrumental record in context. She noted some questions of particular interest to policy makers, including:

- *What is the evidence for temperature, precipitation, or circulation changes, both globally and regionally?*
- *Are climate extremes such as droughts, floods, and heat waves changing, and are they expected to change in the future?*
- *How do patterns of circulation affect climate trends in different regions?*
- *Are these patterns linked to human influences?*
- *How unusual are all of these changes compared to the paleoclimate record?*

Accordingly, one chapter in the AR4 will be devoted to paleoclimate, the past record, and the estimated forcings. Some considerations include:

- *Use of paleoclimatic information to provide greater clarity on what may be natural versus anthropogenic (globally and regionally)*
- *Description of what happened in the past and why – focus on observations and processes*
- *Discussion of paleoenvironmental measurements in greater depth - tree rings, sediments, ice cores, etc. How warm was the so-called Medieval Warm Period? What is the uncertainty? Etc.*
- *Illumination of key vulnerabilities to changes in forcing, and the use of the paleoclimatic perspective as a basis for testing cause and effect relationships*
- *More careful analysis of how anomalous the last century has been – e.g., in terms of drought*
- *Review/ update what is known of abrupt climate changes – the potential wild card*

Solomon expressed the hope that the workshop would provide new insights on drought occurrence, persistence, and analysis from the instrumental and paleoclimatic records; new insights on role/origin of SST and circulation changes (particularly for Africa, North America…but also elsewhere); views on role of land surface, soil moisture, etc. and ability to model them; thoughts on what observations to compare to models and how to analyze models; paleoclimate drought analogues/differences - key insights to processes, persistence, mechanisms, etc.; insights into the role of radiative forcing, aerosol effects on clouds or surface energy budget, and to what extent the droughts of the modern era could be related to human influences.

3.2. Instrumental and paleoclimatic records of drought

The severity and extent of drought in the United States since 1900, summarized by R. Vose and colleagues from NCDC, were greatest during the Dust Bowl years of the 1930s. Because of the size and severity of the episodic events of that decade, succeeding droughts have typically been compared to conditions in those years, particularly conditions during 1934 and 1936. The decades of the 1950s and 1960s were also characterized by several episodes of widespread severe drought. The succeeding decades of the 1970s and 1980s as a whole were unusually wet and above average across much of the United States. However, severe drought episodes affecting large parts of the country occurred in each of those decades. As recently as the late 1990s and succeeding years, more than one-third of the contiguous United States was in severe to extreme drought. Drought conditions persisted over the South and parts of the East through much of 1998-2002, and drought that began in the West in 1998 has persisted in many areas through at least the summer of 2003. D. Cayan emphasized the importance of very few storms or precipitation events being responsible for the difference between dry versus wet years. He also noted that dry years tend to cluster together more than wet years.

Globally, as summarized by A. Dai, drought area increased more than 50% during the 20th century, largely due to the drought conditions over the Sahel and southern Africa during the later part of the century; while changes in wet areas are relatively small. Dai brought his global record of Palmer Drought Severity Index (PDSI) up to date to cover 1870 to 2002 and showed the dominance of precipitation variations in its spatial and temporal variability. His analysis of variability (Figure 2) made use of Empirical Orthogonal Function (EOF) analysis. The first principal component time series depicts a trend. For the 20th Century it highlights the increasing drought in the Sahel, and the general increase in wetness over the United States and other higher latitude regions. The red curve on the lower left panel (Figure 2) is the Darwin sea level pressure anomalies as an index of El Niño Southern Oscillation (ENSO) and is highly correlated with the second principal component 0.72. This highlights the fact that floods and droughts go hand-in-hand, with droughts favored in some areas, such as Australia and much of Africa during El Niño, while wet areas are favored elsewhere, such as the southwestern United States, and these tend to switch during La Niña in the tropics and subtropics.

Heterogeneous landscapes require high density observations to monitor their precipitation and soil moisture adequately (H. Diaz), but most observations are at lower elevations and are not uniformly distributed. It was generally noted that often daily and especially hourly data are much needed to analyze precipitation characteristics (frequency, intensity etc) and are often not available. D. Olago’s written abstract and presentation (by R. Odingo) noted the merits of monitoring tropical glaciers as indicators of climate and precipitation. S. Nicholson expanded on African drought phenomenology, noting its seasonal variations, correlations to SST, and links to the African Easterly Jet. A. Allali detailed the structure of droughts in the Moroccan area and noted links to the North

Atlantic Oscillation (NAO). J. Wei noted the disastrous effects of droughts in northern China, a drought prone area where 60% of the weather-related disasters are due to drought. D. Gochis summarized a CLIVAR-GEWEX research field program on the North American Monsoon Experiment (NAME). Extreme drought in the Yaqui Valley of Mexico (D. Battisti) was suggested to depend more on winter precipitation, which is at odds with current perceptions, and in turn depends on Pacific SST anomalies. Wheat yield there was suggested to be linked more to cloudiness and sunshine than precipitation, in part because of irrigation.

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, such as the current Sahel drought, are not uncommon, and that this scale of drought has been eclipsed in the past by droughts lasting a century or more (J. Overpeck). Thus, the full range of drought variability is potentially much larger than what we have seen in the last 100 years.

For example, in North America (C. Woodhouse), Dust-bowl length events occurred, on average 1-2 times per century, and longer 10-25 year events occurred as well. A drought lasting over 20 years across much of the coterminous U.S. occurred in the late 16th century, and it appears that droughts in the Sierra Nevada region have lasted over 100 years in the past. Abrupt shifts in drought variability have also occurred for poorly understood reasons. The most detailed reconstructions of past North American drought, especially through the PDSI, have been realized through analysis of tree rings (Hughes, Stahle, Betancourt, Meko), and have resulted in a new paleodrought atlas (Woodhouse). Strong complementary and supporting evidence is also present from limnological indicators on lake levels (S. Fritz), eolian sand deposits (S. Forman) indicating dune reactivation (exploiting new luminescence dating techniques that do not depend on the presence of organic matter; S. Forman), and potentially speleothems from caves (J. Cole). Tree ring and eolian evidence (S. St. George) and sediments to deduce lake levels (B. Cumming) were also used to document drought in Canada. Prolonged periods of drought are common features of the Canadian prairie with rather abrupt onset. Western Canadian drought appears to be linked to Californian drought by means of the Pacific Decadal Oscillation (PDO) (G. MacDonald).

Paleoclimatic evidence of floods is compromised by the fact that new floods often wipe out evidence of older floods (K. Hirschboeck). Nevertheless, evidence suggests that floods can occur in the midst of a drought. Similarly, extreme flood and drought can exist side by side in adjacent regions (dipole structures in precipitation anomalies can arise from shifts in storm tracks), and there seems to be a natural upper limit to the magnitude of floods (which may relate to geographical features of basins). Floods also depend a great deal on drainage basin properties. Persistence of weather patterns often seems important in flooding so that saturation of soils, presence of snow, and sequences of storms matter.

It is apparent that mega-droughts in the past have had major impacts on civilizations, and the best example presented (D. Hodell) was the convincing evidence from closed basin lakes in the Yucatan peninsula of Mexico that a series of three droughts in 810, 860 and

910 A.D. led to the collapse of the Maya. "The difference between life and death for the Maya was water" (Gill 2000).

Paleo-droughts were documented in China (Z. De'er) and India (G. Pant), as well as Africa (J. Overpeck, T. Johnson). Links to South American drought were also discussed, although data are still too sparce for a complete picture to emerge from either Africa or South America. The work of D. Verschuren provided a solid base for the African studies, complemented by several studies from lakes (Malawi, Victoria, and Bosumtwi (Ghana)) that provide good evidence of past variations on the migration of the ITCZ and the strength of the monsoon.

3.3. Drought processes and modeling

There is nearly always drought somewhere in the continental United States. Drought is thus a natural phenomenon, although the possibility of human influences cannot be overlooked. Moreover, droughts wax and wane in extent and duration often in an apparently random manner. However, scientists have determined some underlying patterns and also some causes of those patterns. The biggest source of drought world-wide so far identified is the El Niño phenomenon (Figure 2). During El Niño events, drought is endemic in Australia, Indonesia, southeast Asia, northeast Brazil, and parts of Africa. During La Niña events, the preferred locations of droughts shift to other parts of the world, including both North and South America (including the United States). More generally, changes in global 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. There is also good evidence that changes in the land surface, whether caused by humans or by the changing climate, produce amplifying effects, especially in summer (R. Dickinson, X. Zeng). In models, land surface processes are often simplified. It is difficult to depict the full range of heterogeneity that exists in nature. Soil moisture is allowed to vary and is the most important feedback. However, most models do not allow vegetation and ecosystems to evolve, other than as specified by season, and 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 (G. Wang). Some questions were raised about the relevance of the PDSI, as in at least 1 model there is not a good relationship with soil moisture (Rind). It was agreed that PDSI has shortcomings in not accounting for vegetation effects.

Several studies (Hoerling, Schubert, Giannini) suggested that climate model performance has improved to a point where many models are now able to simulate many aspects of the climate of the 20^{th} century when observed SSTs are specified. These include the drying in sub-Saharan Africa (e.g., Figure 3) which is linked mainly to changes in global SSTs and especially the SSTs in the tropical oceans. The recent warming of the Indian Ocean, which has been linked in several analyses to global warming associated with increasing greenhouse gases in the atmosphere from human influences, suggests that Indian Ocean SSTs are playing a stronger role in climate change and may be a major factor in the Sahel drought (Hoerling, Giannini), although perhaps mainly in austral summer. In boreal summer the Atlantic Ocean SSTs and inter-hemispheric SST gradients play a key role but there was some disagreement about the exact role of the Indian Ocean warming in that season. Land surface changes and desertification, which have often been blamed in the past, while important, seem to be feedback amplifiers and not a fundamental cause.

Similarly, the NASA NSIPP model is now simulating the drought in the Great Plains of the United States during the Dust Bowl era from 1932 to 1938 (Schubert) as being associated with changes in global SSTs. In this case, changes throughout the Pacific SSTs (cold PDO-like) are one key ingredient, while changes in the Atlantic SSTs and associated moisture transports into the United States around the Bermuda High are the other. The model correctly simulates the general moistening over the Great Plains in the past 20 years. Again, land surface processes are shown to provide a substantial positive feedback in models. However, Schubert went on to show that the model tends to simulate a Great Plains drought in the 1970s, which was not observed, but was found in 12 out of 14 members of the ensemble. The difficulty in forecasting North American drought is thus revealed by very subtle shifts in the strong atmospheric circulation features in the 2 ensemble outliers. Other studies by Hoerling and colleagues suggest that drying in western parts of the US is internally forced by SST changes in the tropics and especially the Indian and western Pacific oceans. The models also suggest that shorter-term droughts of order a year duration, such as the 1988 North American drought, are largely associated with SST in the ENSO region.

In spite of these successes at simulating droughts, some aspects of the simulations, such as the changes over Mexico in the NSIPP model, are problematic. In general all of these model results rely somewhat on selecting those places and times where the model results appear to agree with observations. However, there are other regions where they disagree.

Several long model runs with unchanging external forcing of the climate have been analyzed in preliminary ways to look for natural incidence of drought. In the NCAR PCM run of 1360 years (Meehl) there were “mega-droughts” (defined as 11 year-average precipitation below normal for over 20 years) about every 140 to 150 years in the Great Basin of the southwest US. Although of modest amplitude, the persistent below-normal precipitation was found to be associated with a cold PDO-like pattern in the model simulated Pacific Ocean SSTs associated with subtropical overturning ocean cells. Mega-droughts in India also occurred in the model with similar frequency and were inversely related to the US droughts, also signaling a link to Pacific SSTs. B. Hunt has run the Australian CSIRO coarse resolution model for 10,000 years with no external forcing anomalies, and found that very few sequences of dry years ever exceed 12 years in duration anywhere. In other words, it was found in this particular model that extended dry periods typically have one or two wet years interspersed.

Versions of the NCAR coupled model have also been used to look at paleoclimate and drought. A single simulation of the past millennium (C. Ammann) forced by estimates of anomalous volcanic eruption effects and solar variations simulate cooling following major volcanic eruptions and decreases in the hydrological cycle. However, the apparent relationship between increased solar irradiance and decreased precipitation found by D. Verschuren over Africa was the opposite to the model results. Paleomodel results for

Africa 8500 BP using a later version of the NCAR coupled model (B. Otto-Bliesner) reveal that the large changes in orbit of the Earth around the sun, increasing insolation in the boreal summer, enhance land-sea contrast and drive a stronger and 7° farther northward ITCZ over Africa, making for a much wetter Sahel and smaller Sahara desert, much as observed. Interactive vegetation changes, which were not included, would likely magnify these effects even more.

The merits of using regional climate models to simulate effects of small scale features of the landscape, such as mountains, were highlighted by K. Cook and W. Gutowski. But even high resolution models tend to produce too much low intensity precipitation compared with observations. Moisture transport processes were emphasized by R. Seager.

A rising concern is over possible increased drought in the future as the climate changes with increased greenhouse gases in the atmosphere. In this case, the risk arises especially from increased heating ("global warming") that produces increased drying and hence evaporation (if moisture is available, i.e., Figure 4). 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 (Trenberth).
As the climate warms, the atmosphere can hold more moisture, and precipitation is likely to increase in winter, but with more falling as rain rather than snow. Increased melting of snow further adds to the likelihood that snow pack in the mountains and on the plains is less as spring arrives, making less melt water as the summer looms. Drier soils mean less evaporation and so the heat goes into higher temperatures, less recycled moisture in the atmosphere, and hence less rain during summer. With increased drying, it is a recipe for increased intensity, frequency and duration of drought. Increased heat waves and risk of wildfire follow. These mechanisms were found to occur at steady state in the new version of the GFDL model (T. Delworth), leading to increased risk of summer continental drought. However, SST patterns influence atmospheric circulation patterns such as the North Atlantic Oscillation (NAO) that can also modulate these effects, particularly in transient climate simulations. Experiments suggest that SST is the dominant control on atmospheric circulation patterns, but with soil moisture changes making important local contributions.

4. Breakout Working Groups

4.1. Introduction

The overall goals of the three working groups were to summarize knowledge with regard to drought and highlight ways of improving understanding, analysis approaches, and predictive capabilities for drought from a focus on new ideas, observations, analyses, theories and model studies. Special emphasis was to be given to *both* the instrumental and paleoclimatic records of drought.

Breakout Group 1 Focus: What can the instrumental and paleoclimatic record tell us about droughts, their historical distribution, duration, impacts on societies, and abruptness of onset or end? How good are proxy records and what might be done to make them better? Are there forcings that are identified with droughts or do they occur or climate regimes change without obvious links to external forcings? What are the implications for IPCC? What are the implications for future research?

Breakout Group 2 Focus: What can climate models and our understanding of processes tell us about droughts, their distribution, duration, impacts on societies, causes, and prospects for the future? What physical processes appear to be well enough understood to allow an understanding of droughts in different regions? For example, is the understanding of land surface processes and its uncertainties likely to be equally important in all regions? What about precipitation, trends in SST, or trends in patterns such as the NAO? Are there particular regions where the ability to understand and predict drought is more limited by process understanding than in others? What improvements in process level understanding are needed? What are the implications for IPCC? What are the implications for future research?

Breakout Group 3 Focus: What can the paleoclimatic record, the instrumental record, modeling results and understanding tell us about abrupt climate change, especially with regard to droughts in warm climates? Do the records and/or models give us insight into abrupt climate change as manifested in droughts? How relevant is the past record during glacial periods to abrupt change in future climate? Are abruptness of onset or end of droughts local, regional or widespread climate change manifestations? What are the implications for IPCC? What are the implications for future research?

The outcome of the three breakout groups were given in reports in plenary and more general discussion followed.

4.2. Summary of final plenary and general recommendations

Wide-ranging discussions occurred on definitions of drought, how good the observational record is, 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 (which is relevant for smoothed or blurred records without high resolution).

Considerable discussion was on improving the paleo-drought record, covering such topics as:

- *Site replication*
- *Spatial distribution of sites*
- *Chronologies and temporal resolution*
- *Data limitations/validity of paleoclimate data (uncertainty, error)*
- *Implicit time averaging of some paleorecords*
- *Calibration/verification issues*
- *Qualitative (warm-cold, dry-wet) vs. quantitative*
- *Can we get at intensity, frequency, amount of precipitation (snow vs. rain?).*

It was concluded that the paleoclimatic record is important for placing 20th century droughts into a long-term context. The paleoclimatic record can provide information about range of drought variability under natural climate variability, which is important for assessing whether the frequency and severity of 20^{th} century droughts are outside the range observed in the past. The last 200-300 year time frame is data-rich, and important for calibrating/validating paleo proxies with historical data. However, there is a need to consider the whole Holocene to evaluate drought variability during a warm interglacial period. Spatial patterns and temporal variability are important for understanding mechanisms.

> <u>General Recommendation 1:</u> *a "Tiger Team" should be established that is paleo led to produce improved estimates of the uncertainties present in paleoclimatic data and to create interdisciplinary meta-data standards that will foster more/better use of paleoclimatic data by paleoclimatologists and non-paleoclimatologists alike. It should review proxies and what we do and do not know, especially with regard to droughts (intensity, duration, extent etc).*

Several results were presented regarding the utility of examining the base state of the climate (e.g., the East African Jet and the ITCZ) as it compares to models. Discussion occurred on how to use this information to screen out some models as being unsuitable, a point that IPCC should also consider. However, it is important that the screening should be with models that are run with all forcings in order to properly compare with the observational record. Using SSTs alone is not enough. In general discussion in plenary after the WG reports, several recommendations were made.

> <u>General Recommendation 2</u>: *Modeling groups should be approached to suggest that certain projects should be undertaken. The approach could either through coordinated projects, such as the Coupled Modeling Intercomparison Project (CMIP) or the Climate of the Twentieth Century (C20C) project, or through international working groups such as the Working Group on Coupled Modeling (WGCM). Questions that should be addressed include the following:*
>
> - *Do uncoupled models simulate the 20^{th} Century Sahel drought?*
> - *Do coupled models simulate the Sahel drought?*

- *If not, why not?*

  For instance several models with specified SSTs do simulate the drought, hence it is related to boundary forcing of the atmosphere, so one key question for uncoupled models is whether the climatology simulated over Africa, especially of the ITCZ and Sahara, are adequately represented? For coupled models a key question is whether the global SST patterns of change are adequately depicted?

- *How realistically do coupled models simulate drought?*

  This topic is to systematically analyze long runs of climate models for information on droughts, and compare results with the paleoclimatic record, especially in cases where the last millennium has been simulated with estimated forcings applied, but also in unforced runs.

<u>IPCC Relevance</u>: Much of the workshop touched on the topic of IPCC relevance. Some specific points and questions highlight relevance to AR4:

- *Prolonged, intense droughts have happened in the past*
- *IPCC should consider clear examples of past severe drought from many regions*
    - *Paleoclimatic data are convincing: this can (will) happen*
    - *Droughts get more attention than small global temperature increases among national policymakers (as well as most stakeholders)*
- *How often did past droughts occur?*
    - *North America: two decadal droughts per century*
    - *North America and Northern Africa: one century-scale drought per millennium*
- *Droughts are becoming more spatially coherent (since 1976)*
- *Droughts can (will) occur regardless of human intervention – profound impacts*
    - *Many regions, including the most vulnerable*
- *Is the human influence on climate making them more or less likely?*
- *We can make progress by understanding what caused past droughts*
- *Has the 1976 climate shift reversed? We do not know.*
    - *Drought more likely in some areas*
- *How abrupt is "dangerous", and what would we do with warning? Is it possible to establish an early warning capability?*
- *How reliable are predictions of future continental desiccation?*
- *Intensification of hydrologic cycle: will both more drought and more flooding accompany future change?*

4.3. Summary from Working Group 1: observations and drought *(Co-chairs C. Woodhouse, B. Garanganga; Rapporteur D. Hodell)*

This working group discussed a range of topics related to instrumental and paleoclimatic records of drought. The paleoclimatic records of drought are many and varied, each with its own characteristics, strengths, and weaknesses. Much discussion focused on how to use these records together to document and describe drought events, and to further our understanding about causal mechanisms. The ability to understand the information data are conveying with respect to drought, and the uncertainties in the data related to the interpretation and the dating, were key issues. The group recommended a concerted effort be made to improve the quality of data, target collections of new data in areas critical to understanding drought, and to enhance the usability of the data by groups such as the IPCC and decision-makers.

4.3.1. Working Group 1 findings

1. Paleoclimatic records of drought are critical for assessing the extent, severity, duration and frequency of 20th century drought events over the longer term and under naturally varying climatic conditions.

2. As presently understood, there is little evidence for external forcing of the most severe droughts identified in the paleorecord of the last millennium. Internal forcing of such droughts by SST variations may or may not be externally forced. A handful of climate simulations runs that exceed 1000 years or more suggest that extreme droughts could be inherent to the climate system without external forcing. Although we cannot presently rule out external forcing, modern boundary conditions are probably not different enough from the past 1000 years to rule out recurrence of the most extreme droughts. Although the past climate will not be an exact analogue to the future, analysis of past drought events can provide insights on causal mechanisms and impacts of drought in a future warm climate.

3. The definition of drought is both context- (related to impacts), and proxy- (related to spatial and temporal scales of proxy record) dependent, and thus there is not one definition of drought. The term megadrought, which is in popular use, has not been rigorously defined and can mean many things to many people. Nevertheless, the term has some usefulness in providing a frame of reference for comparing prehistoric with historic droughts. For example, drought area indices can be derived from a blend of instrumental records and gridded tree-ring reconstructions for the past 500-1000 years. In the conterminous U.S., the instrumental drought area index of severe drought (the percent area experiencing $\leq$ -3 PDSI) indicates that single-year events of >30% area affected are always embedded in multiyear droughts. In the instrumental record, the most severe and longest droughts in the conterminous U.S are also the most extensive- e.g., 1931-1938 and 1951-1956. For comparative purposes then, a megadrought could be defined as those events that equal or exceed the magnitudes, duration and extent of the 1930's and 1950's droughts. This

definition would apply only to the conterminous U.S., but one could envision how other definitions might be derived similarly elsewhere.

4. Although the temporal variability characteristics of drought are important to define, drought location and extent are also important, and especially key for identifying causal mechanisms.

5. The climate modeling community has successfully used observed SST variations to simulate droughts in the past 100 years. Likewise, paleoclimatic records of sea surface temperatures and climatic conditions in the tropics are becoming increasingly necessary to drive GCM simulations of past droughts, and determine their causes.

6. Periods of breaks within a drought, as well as periods of surpluses, are important in studies of drought, both of which could be useful for planning and management. For example, one adaptation to drought and greater societal demands for water might be to develop and institutionalize measures for forecasting, banking and using precipitation and runoff on short notice during periods of breaks within an extended drought. Both the instrumental and paleorecord of precipitation could be used to understand the causes and probabilities of breaks within droughts.

7. The IPCC presents an opportunity for the paleoclimatology community to make an important contribution to the study and assessment of present and future climates, to demonstrate the credibility and value of paleoclimatic data, analysis and results, and to clearly communicate and substantiate those results.

4.3.2. Working Group 1 recommendations

Data usability and enhancements

These recommendations may best be acted upon by holding a workshop to organize these efforts, and establish a working group, within the paleoclimatology community.

1. A peer-reviewed, published review of proxy drought data should be generated that outlines the strengths and weakness of each proxy, quantifies uncertainties (dating), spatial and temporal resolution, and the strength and type of response function (i.e., identification of the environmental variable to which each proxy is responding). The goal of the review would be to enhance the usability of paleoclimatic data by clearly communicating how each proxy data type should be used and interpreted.

2. The uncertainty related to data that provide qualitative data should be reduced by generating a template or set of metadata standards. A main feature should include an assessment of the data or method of scaling that enables different records to be compared and assessed for consistency, which will help estimate uncertainty in these records. Metadata should also include the items mentioned in #1. These metadata should be included along with the data in archives and appendices.

Research

These recommendation should be highlighted as priorities in programs that fund paleoclimatic and global change research.

1. The paleoclimate community should aim to develop synthetic approaches that can be applied in deeper time. An obvious foundation for such studies are the last 200-300 years, which are data-rich, with early instrumental, historical, and tree-ring data, and wide spatial coverage. The coverage will enable spatial mapping to examine widespread patterns of drought. These instrumental data and high resolution, precisely dated proxy data also provide an excellent foundation for the calibrating less-precisely, lower resolution, or data with a drought signal that is not yet well defined.

2. Synthesis studies of high resolution drought proxy records for the last millennium should be undertaken to better document the temporal and spatial characteristics of key drought events identified (e.g., the so-called Medieval Warm Period and late 16^{th} century) as well as others that may not yet have been identified. These high-resolution drought proxy records should be exploited to identify temporal and spatial statistics of droughts over the long term, as well as determine the causes of the most severe droughts. A key goal for the paleocommunity should be to develop and integrate independent paleorecords of drought and sea surface temperatures.

3. The paleocommunity should focus on drought events and periods of aridity during the Holocene such as the 8.2ka and 4.2ka events, and emerging evidence for prolonged periods of aridity such as 2.7-1 ka in disparate regions such as the central Rockies, the northern Sierra Nevada, northern Europe and the Caribbean.

4. Collaborative research between paleoscientists, modelers, and climatologists should be accelerated to investigate the ability of the models to simulate drought, duplicate location and extent, duration, recurrence and other drought properties in paleorecords, exploit models for causal mechanisms, and to test models for vegetation/land cover/drought interactions that are regionally focused.

Improvements in research methodologies

These recommendations include activities that have traditionally been difficult to fund, as many will not yield exciting new science. These tasks are nevertheless necessary for enhancing the quality and usefulness (especially for applications such at the IPCC), and deserve special recognition by funding agencies. Some efforts are currently underway to address some deficiencies in the observational data, and a paleo-observing network initiative is in some stage of development (i.e., GPOS, the Global Paleoclimate Observing System; http://www.pages.unibe.ch/about/research/initiatives/gpos.html).

1. Modern process studies should be undertaken to calibrate proxy records with climate variables to quantify proxy response to climate, and to drought, in particular.

2. Increased replication and better chronology development is needed at both existing data collection sites and new sites to improve data quality.

3. Out-of-date tree-ring collections (ending in 1960s-80s) in critical locations should be resampled to bring up to date.

4. Techniques and standard methods for blending tree-ring, historical, instrumental data should be developed (some work has been funded under CCDD, and this is still a program focus).

3. Instrumental climate records that are in danger of being lost, especially in Africa need to be rehabilitated (data rescue of paper copies, poorly stored and organized, undigitized).

4. Efforts should be made to make historical data, for Africa in particular, available. These data are an valuable source of information on past droughts.

5. Observational climate networks should be expanded to poorly monitored regions (e.g., mountain areas), to measure key drought-related variables not currently being recorded (e.g., soil moisture, evaporative flux, surface irradiance) and existing networks of long term data collections (e.g., streamflow) should be maintained.

6. New proxy data should be collected in areas that are centers of action with regard to drought causal mechanisms (e.g., Indian Ocean), or sensitive to extremes in climate or vulnerable to climate change impacts (e.g., high latitudes, elevations)

7. High-resolution proxy records that reflect tropical climate and SSTs (corals, high sedimentation-rate marine records, tree-ring isotopes) should be developed.

8. Targeted collections should be carried out in other areas that currently lack paleo-drought data (e.g., Asia, S. America, Africa) and with paleoclimatic data that have shown promise as drought proxies, but have not yet been widely exploited, such as speleothems.

4.4. Summary from Working Group 2: Modeling and processes *(Co-chairs K. Cook and T. Delworth; Rapporteur D. Gochis)*

This working group covered a wide range of issues related to the climate system mechanisms related to drought. Many questions were raised that warrant further research:

- *How do oceans and land differ in their responses to external forcing (e.g., time scales, phasing, and amplitude), and what are the implications for hydrologic variability?*
- *What is the role of vegetation in initiating and sustaining drought (especially wilting vegetation, mineral dust loading from dead vegetation regions)?*

- *Based on the 20th century simulations, to what extent do SST trends and variability force drought (by region)? Do we understand within each region what the feedback is with the land?*
- *When a majority of ensemble members show meaningful deviation from climatology, does each member represent the same physical processes?*
- *To what extent do simulations with SST anomalies produce drought behavior in regions outside N. America/Sahel?*
- *Are models capturing the dynamics of late 20th century drought? (e.g., blocking patterns)? What are the relationships/differences between short- and long-term droughts?*
- *Given the apparent importance of the Indian Ocean in forcing drought, what is the future outlook for Indian Ocean SSTs?*
- *Can GCMs simulate large-scale wet events as well as they appear to simulate large-scale dry events when forced with observed SSTs?*
- *Does the current generation of models indicate increased mid-continental summer drying in response to increasing greenhouse gases? Can smaller scale physical processes modify this result?*
- *Given the importance of SSTs for drought, is there any predictability of SSTs beyond the seasonal time scale, which could be of relevance for drought predictions?*

There is a need to assess the internal variability of droughts in coupled models, and the potential for interaction between internal modes and external forcing. There is also a need to consider how this may change in the future.

4.4.1. Working Group 2 findings

1. Some models simulate drought in N. Africa/America in response to the time series of observed SSTs in the 20th century.

2. Some models have shown skill in simulating tropical drought and extra-tropical summer drought.

3. Model simulations show that land surface processes (e.g., vegetation dynamics) can play an important role in sustaining drought.

4. Coupled models can generate decadal-scale droughts (i.e., “mega-droughts”) from internal dynamics.

5. While time-mean precipitation patterns are well simulated, many higher order properties are not well reproduced (e.g., intensity, duration, frequency, diurnal cycle).

4.4.2. Working Group 2 recommendations

1. Develop a list of regionally specific diagnostics for models focused on drought, e.g.,

- *Assess influence of near coastal (up to 500 km) SSTs on drought, and model performance*
- *Identify critical regional features and their influence on observed and simulated climate*
- *Assess the diurnal cycle of precipitation and associated fields*

2. Carry out experiments to identify timescale of coupling between ocean and land.

3. Determine the physical mechanisms by which models simulate SST-induced droughts.

4. Investigate the evaporative response to increased heating in the various models.

5. Create metrics characterizing hydrologic states that are common across the modeling, diagnostic and paleoclimate communities. These characteristics should include intensity and duration. (Is PDSI adequate or appropriate?).

6. Assess the inter-model consistency of increased mid-continental drying under warming scenarios.

7. Assess predictability beyond seasonal timescales.

8. Determine potential changes in tropical storm activity with respect to drought termination.

9. Need a paleo-SST reconstructions (minimum 500 yrs).

4.5. Summary from Working Group 3: Abrupt climate transitions *(Co-chairs M. Cane, G. Pant; Rapporteur J. Cole)*

Considerable discussion occurred about the definition of abrupt climate change. Some conclusions include the view that this cannot be defined with respect to forcing as droughts may be “unforced”. In crossing a threshold to a new regime, the transition time must be short relative to duration of the regime, and the change must be sustained. It was noted that it can include a change in character of variability perhaps such as seems to have happened in Europe in 2002 (floods) and 2003 (heat waves). The time scale of interest is multiyear and longer. Examples in the instrumental record include:

- *1960s Sahel drying*
- *1976 climate shift in Pacific and ENSO*

4.5.1. Working Group 3 findings

1. Climate can respond as an abrupt transition rather than gradual change.

2. National Academy Report, 2002: Abrupt change is important, big impacts, low (no) predictability.

3. Drought has been seen to respond abruptly.

4. There are periods of prolonged drought in paleoclimatic records that cannot be explained by known radiative forcings or internal mechanisms of the climate system.

5. We expect that unanticipated severe drought will be a feature of climate in the near future, as it has been in the past.

6. Direct relevance of the glacial-era record to abrupt climate change is hard to defend: conditions today and in the future are different.

7. Large droughts overwhelm standard mechanisms for coping even in developed countries (e.g., inter-basin water transfers).

8. Models reproduce multi-decadal droughts in specified SST runs, but not as a direct response to forcing in coupled models.

4.5.2. Working Group 3 recommendations

1. Improve integration of observations, paleoclimate and model studies – need global perspective.

2. More targeted paleoclimate studies (see below).

3. Quantify role of forcing on drought (solar and others).

4. More priority on documenting/understanding the location, duration, abruptness, synchrony, intensity of past droughts:
    - *How well can we quantify drought from proxies?*

5. Focus more on time series of droughts, including networks of high resolution, well dated, Holocene records:
    - *Characterize recurrence frequencies*
    - *Focus on selected time slices of interest (e.g., see below)*

6. Time slice studies: understand global pattern associated with known large anomalies; spatial information is important for model validation.

7. Times of special interest:
    - *16th century drought: North America*
    - *Medieval: both North America and Northern Africa*
    - *4.2ka: Northern Africa, Middle East and South Asia (Indian Subcontinent to Tibet)*
    - *8.2ka event (African drying, global event?)*

8. Need to cover transitions in and out of key intervals (e.g., see above).

9. Look at global patterns for clues to mechanism(s).

10. Understanding important questions and modeling needs should motivate new work.

11. Asian monsoon variability is a critical aspect of drought research.

12. Important to look at both wet and dry extremes:
    - *Potential for "switching" of land versus ocean precipitation*
    - *Competition for water vapor among regions*
    - *Adequate forcing time series before 20th century are lacking*

13. Coupling with dynamic vegetation and ocean variability is important.

14. Ensembles needed, both forced and unforced.

15. Model output has more credibility when such things are seen to actually have occurred (i.e., via comparisons with paleoclimatic records).

16. Existing long runs at many centers – should encourage other groups to look at output to see if long droughts are a common feature.

5. Supplemental Reading List

Alley, R. B, J. Marotzke, W. D. Nordhaus, J. T. Overpeck, D. M. Peteet, R. A. Pielke Jr., R. T. Pierrehumbert, P. B. Rhines, T. F. Stocker, L. D. Talley, and J. M. Wallace, 2003. Abrupt climate change, *Science*, **299**, 2005-2010.

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

Dai, A., K. E. Trenberth and T. R. Karl 1998: Global variations in droughts and wet spells: 1900–1995. *Geophys. Res. Lttrs.,* **25**, 3367–3370.

Fye, F. K., D. W. Stahle and E. R. Cook, 2003: Paleoclimatic analogs to Twentieth-Century moisture regimes across the United States. *Bull. Amer. Meteor. Soc.*, **84**, 901-909.

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

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

Hoerling, M., and A. Kumar, 2003: The perfect ocean for drought. *Science*, **299**, 691-694.

Hunt, B. G., and T. I. Elliott, 2002: Mexican megadrought. *Clim. Dyn*., ***20***, 1-12.

IPCC (Intergovernmental Panel on Climate Change), *Climate Change 2001. The scientific basis*. Eds. J. T. Houghton, et al. Cambridge University Press, Cambridge, U.K. 881pp.

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

Nicholson, S. E., B. Some, and B. Kone, 2000. An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Niño and the 1998 La Niña years, *J. Clim.*, **13**, 2628-2640.

National Research Council, 2002. *Abrupt Climate Change: Inevitable Surprises*, 182 pp., National Academy Press, Washington, D.C.

Stahle, D.W., E.R. Cook, M.K. Cleaveland, D. Therrell, D. Meko, H.D. Grissino-Mayer, E. Watson, and B.H. Luckman, 2000: Tree-ring data document 16th century megadrought over North America, EOS, Transactions, American Geophysical Union, **81** (12), 121,125.

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

Trenberth, K. E., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change*, **39**, 667–694.

Trenberth, K. E., and C. J. Guillemot, 1996: Physical processes involved in the 1988 drought and 1993 floods in North America. *J. Climate,* **9**, 1288–1298.

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

Trenberth, K., J. Overpeck and S. Solomon, 2004: Exploring drought and its implications for the future. *Eos*, 85, No. 3, 20 Jan. 2004, p27.

Verschuren, D., K.R. Laird, and B.F. Cumming, 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years, *Nature*, 403, 410-414.

Woodhouse C.A and J.T. Overpeck, 1998: 2000 years of drought variability in the central United States *Bull. Amer. Meteor. Soc.*, **79**, 2693-2714.

6. Figures

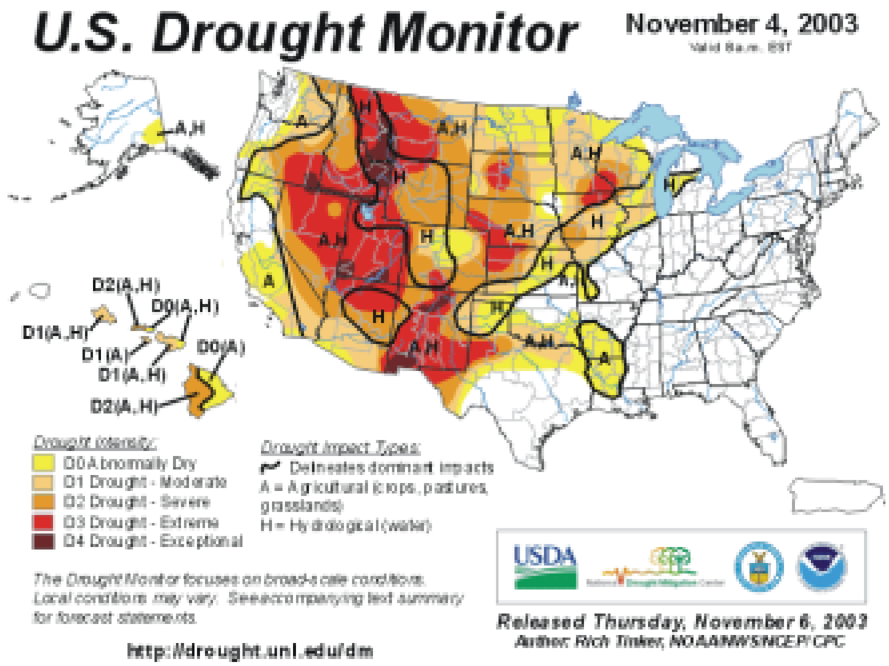

Figure 1. Drought assessment for the U.S. Nov. 4, 2003

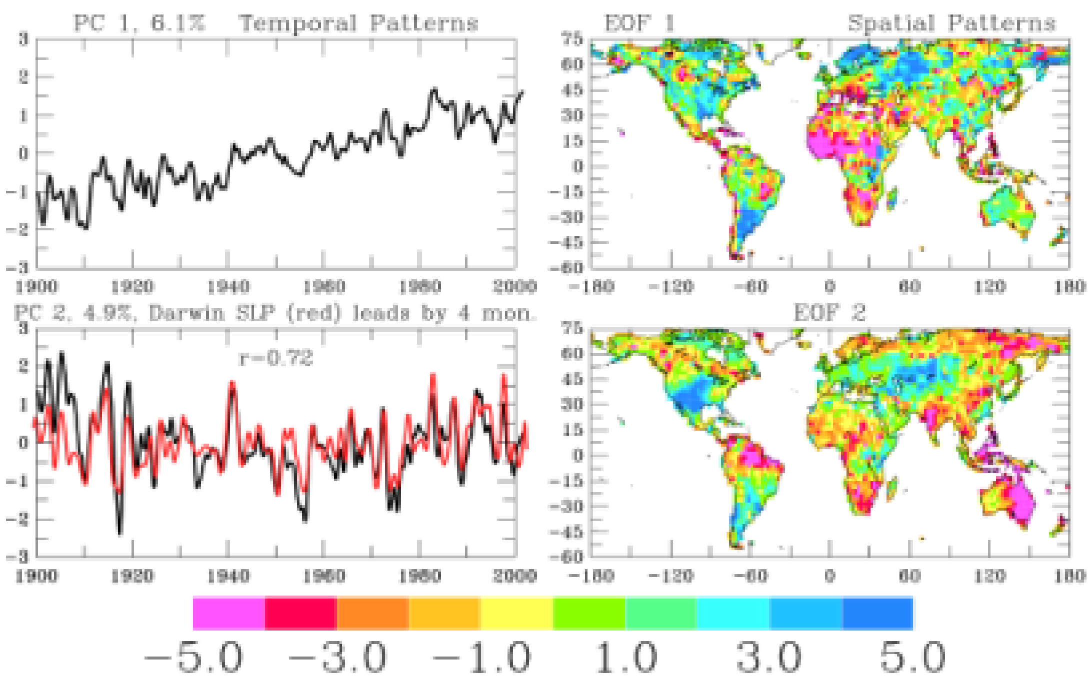

Figure 2. The first two EOFs of the PDSI are shown (right) along with their principle component time series (left), from A. Dai. The first principal component depicts a trend. The red curve on the lower left panel is the Darwin sea level pressure anomalies as an index of ENSO and is highly correlated with the second principal component (r=0.72).

Indices of Sahel rainfall variability. Observations used the average of stations between 10°N and 20°N, 20°W and 40°E. Model numbers were bases on the ensemble-mean average of grid-boxes between 10°N and 20°N, 20°W and 35°E. The correlation between observed and modeled indices of (JAS) rainfall over 1930–2000 is 0.60. (Time series are standardized to allow for an immediate comparison, because variability in the ensemble mean is muted in comparison to the single observed realization. The ratio of observed to ensemble-mean standard deviations in the Sahel is 4.)

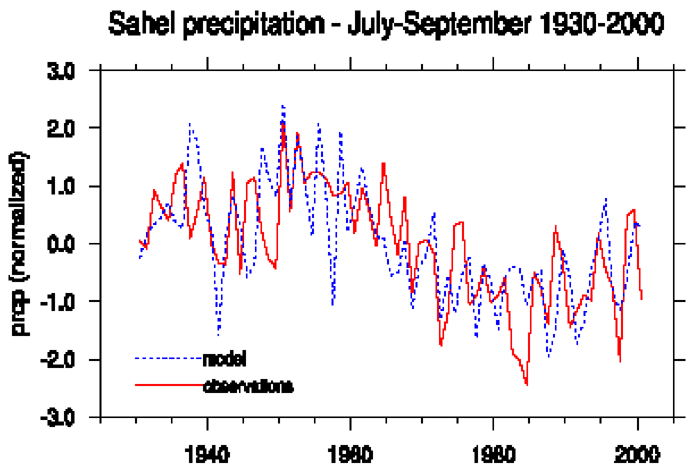

Figure 3. From Giannini et al., Science, 2003.

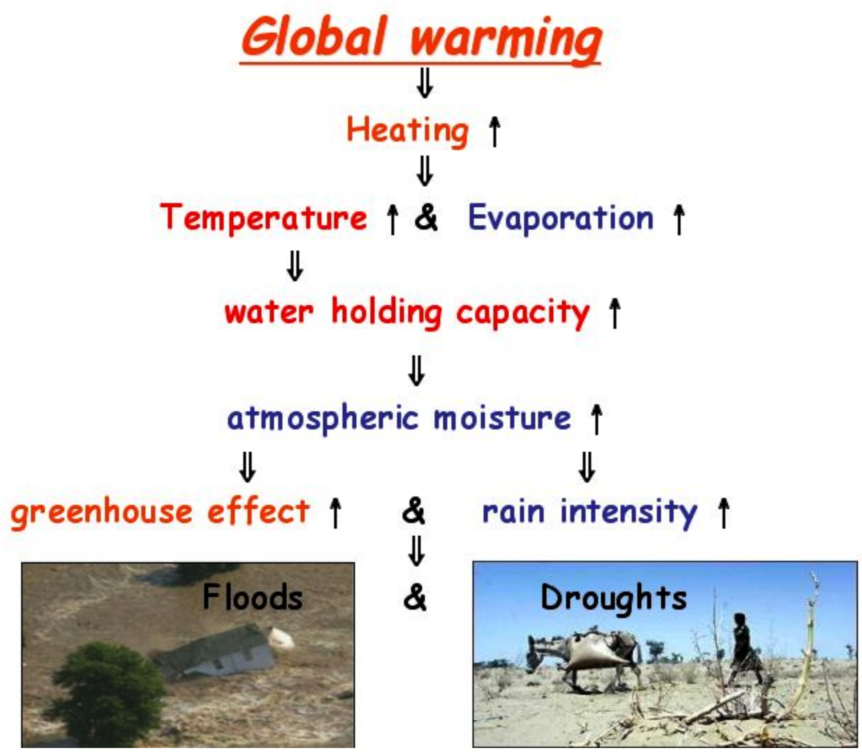

Figure 4. **Future global warming is likely to speed up the global hydrologic cycle, and lead to increase incidence of both floods and droughts. From K.Trenberth.**

Appendix I. Final Agenda

CLIVAR/PAGES/IPCC Workshop
"A multi-millennia perspective on drought and implications for the future"
November 18-21, 2003
Tucson, AZ.

***** The workshop will take place in the Ocotillo and Cholla Rooms *****

DAY ONE – November 18 (Tuesday)

8:00 9:00 Registration/Continental Breakfast
9:00 9:15 Workshop Overview and Objectives (Trenberth)
9:15 9:25 Logistics, etc. (Carochi)
9:25 9:50 Conceptual framework, goals, overview: CLIVAR (Trenberth)
9:50 10:10 IPCC (Solomon)
10:10 10:30 Coffee Break
10:30 11:00 Contemporary Trends in drought on the North American Continent (R. Vose)
11:00 11:20 Global Variations in Droughts and Wet Spells in the 20^{th} Century (A. Dai)
11:20 11:40 The NAME (North American Monsoon Experiment) Research Program (D. Gochis)
11:40 12:00 The Paleo-climate Record of Mountain Glaciers in equatorial Africa (R. Odingo)
12:00 12:20 North African instrumental observations (S. Nicholson)
12:20 13:30 Lunch
13:30 13:50 Conceptual framework, goals, overview: PAGES (Overpeck)
13:50 14:35 Panel 1: Instrumental Record of Drought (Chair, S. Sorooshian)
H. Diaz
J. Wei
D. Cayan
A. Allali (Drought Impacts in Morocco)
14:35 14:50 Discussion of Instrumental Perspectives
14:50 15:10 North American Drought Atlas (C. Woodhouse)
15:10 15:30 SW United States drought: tree-ring perspectives (M. Hughes)
15:30 16:00 Coffee Break
16:00 16:20 16^{th} Century Megadrought: Convergence and Propagation of Decadal Drought Modes Over North America? (D. Stahle)
16:20 16:40 Lancustrine Perpsectives on Late-Holocene Drought in the North American Continental Interior (S. Fritz)
16:40 17:00 Deciphering Eolian Sand Depositional Records from the Western Great Plains in the Past 2000 years: Landscape Response to Extreme Drought (S. Foreman)

18:00 22:00 Reception at hotel (cash bar)

DAY TWO – November 19 (Wednesday)

8:00 8:30 Continental Breakfast
8:30 9:50 Panel 2: Paleoclimate Record of North American Drought (Chair, G. MacDonald)
J. Betancourt – AMO, PDO< and Severe Droughts in the Conterminous US: a Southwestern Perspective

J. Cole – ENSO – US Drought relationships
D. Meko – Multi-Basin Hydrologic Drought
D. Hodell – Drought and the Collapse of the Classic Maya Civilization
G. MacDonald – Canadian/California Drought
S. St. George – Tree Ring and eolian Evidence for Hydroclimatic Variability in Western Canada During the Last Several Centuries

9:50 10:05 Discussion of North American perspectives
10:05 10:25 Floods, Paleofloods, and Drought: Insights from the Upper Tails (K. Hirshboeck)
10:25 10:55 Coffee Break
10:55 11:55 Panel 3: Paleoclimate Record of other Drought (Chair, J. Overpeck)
T. Johnson – East African Drought
J. Overpeck – A new perspective on hydrologic change in West Africa over the last 800 years
G. Pant - Drought in India
D. Zhang – Drought Change and Severe Events in the Past Years of China
11:55 12:30 Discussion of Paleoperspectives
12:30 13:50 Lunch
13:50 14:10 Mechanisms for Land Surface Feedback on Drought (R. Dickinson)
14:10 14:30 Drought Occurrences in West Africa: Role of Vegetation Dynamics (G. Wang)
14:30 14:50 Mechanisms and Teleconnections of Drought in the Great Plains (S. Schubert)
14:50 15:10 Mechanisms and Teleconnections (D. Battisti)
15:10 15:30 20th Century African and Mediterranean Drying: Regional Responses to Greenhouse Gas forcing (M. Hoerling)
15:30 15:40 Discussion
15:40 16:10 Coffee Break
16:10 16:30 Interannual to interdecadal variability of Sahel rainfall in the NSIPP1 AGCM (A. Giannini)
16:30 16:50 Long-term Droughts in the North American and South Asian regions in a 1000-years Global Coupled Model Simulation (G. Meehl)
16:50 17:10 Characteristics of exceptional Drought Events From a 10,000-year Climatic Simulation (Hunt)
17:10 17:30 Continental Summer Dryness in the New GFDL Climate model (T. Delworth)
17:30 17:45 Discussion

DAY THREE – November 20 (Thursday)

8:00 8:30 Continental Breakfast
8:30 8:50 Paleomodeling of Drought in Northern Africa (B. Otto-Bliesner)
8:50 9:10 Paleomodeling (C. Amman)
9:10 9:30 Characterization of Drought in Past and Future Climate (D. Rind)
9:30 10:15 Panel 4: Modeling and Paleomodeling (Chair: K. Trenberth)
R. Seager - Tropical Modulation of Mid-Latitude Eddies and the Causes of Extratropical Precipitation Variability
K. Cook – Modeling and Paleomodeling
X. Zeng – The Role of Land in Drought
10:15 10:45 Coffee Break
10:45 11:20 Panel 4 Follow-up Discussion
11:20 12:10 Establishment of Breakout Groups
12:10 13:30 Lunch

13:30	17:30	Breakout Groups Meet Group #1: Connie Woodhouse & Brad Garanganga/co-leaders, Brian Cumming/rapporteur Group #2: Kerry Cook & Thomas Delworth/co-leaders, Dave Gochis/rapporteur Group #3: Mark Cane & G.B. Pant/co-leaders, Julia Cole/rapporteur

DAY FOUR – November 21 (Friday)

8:00	8:30	Continental Breakfast
8:30	8:40	Plenary Overview
8:40	9:00	Breakout Group 1 Report
9:00	9:20	Breakout Group 2 Report
9:20	9:40	Breakout Group 3 Report
9:40	10:30	Discussion
10:30	11:00	Coffee Break
11:00	12:00	Discussion, report Planning and Wrap-Up

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