Summary Report of the Workshop on:

Observational and Modeling Requirements for Predicting Drought on Seasonal to Decadal Time Scales

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Table of Contents

Executive Summary

A workshop was held in May of 2005 to determine what is needed to accelerate progress on drought prediction with a focus on developing capabilities and products that facilitate water management and agricultural applications for the Americas. The more than 100 participants included experts in both drought research and applications, and spanned the drought communities of the United States, Canada, Mexico, Central and South America and Australia. Support for the workshop was provided by the NASA programs on Modeling, Analysis and Prediction, and Terrestrial Hydrology, and NOAA's Climate Prediction Program for the Americas. A key interest of both agencies was that the workshop provide input on research priorities for their planning activities for the National Integrated Drought Information System (NIDIS).

The key recommendation of the workshop is that **an interagency (NASA, NOAA, NSF, DOE) drought research program should be initiated that would focus ongoing and new drought-related research on the definition, predictability, and prediction of drought, and on the utilization of this information by stakeholders.** It is further recommended that the program be established within the next three years as a central part of the agencies planning activities for NIDIS. A drought prediction consortium (action 1 below, and described further in the Appendix) is recommended as a high priority initial coordinating and focusing activity of the program. The program would consist of the following three elements:

- **SHORT-TERM DROUGHT PROBLEM:** improved definition, attribution and prediction on sub-seasonal to interannual time scales.

  Action 1: Form a national consortium of prediction centers and drought researchers that would use existing tools/models and observing systems (monitoring) to assess the quality of monthly to interannual forecasts of precipitation and other hydrological quantities. This consortium would also investigate the impact of new observations and the utility of new forecasting techniques (such as multi-model ensembles), perform observing system sensitivity studies related to hydrological variables, and make recommendations for the improvement of observing systems and modeling/assimilation systems.

- **LONG-TERM DROUGHT PROBLEM:** improved understanding of the mechanisms of decadal drought and its predictability, including the impacts of SST variability, deep soil moisture variability, and the impact of global warming.

  Action 2: Consolidate multi-agency research efforts into a program that will address the mechanisms that control the land surface branch of the hydrological cycle at decadal timescales. The program would include basic research on the causes of historical droughts and would assess the usefulness of coupled climate models for drought-related diagnostic and predictability studies. The program would also support the use of paleodata for improved estimates of current drought risk and would assess potential effects and implications of long-term drought predictions for policy/planning/etc.

- **UTILIZATION OF DROUGHT PREDICTIONS:** Transition of improved monitoring/prediction/attribution tools to operations; a bridging of the gap between hydrological forecasts and stakeholders (utilization of probabilistic forecasts, education, forecast interpretation for different sectors, assessment of uncertainties for different sectors, etc.).

  Action 3: Provide a focal point among agencies with drought research interests that will facilitate transition of research advances into operations. It should support interaction with the user community (e.g., NIDIS) to define aspects of drought that are most useful to predict and improve how drought information is conveyed, and it should foster collaboration/ coordination with neighboring countries (e.g., the new Canadian Drought Research Initiative)

Specific research and observational needs for each element of the program are detailed in the text.

I. Background

Drought, especially prolonged multi-year drought, has tremendous societal and economic impacts on the United States, and many other countries throughout the world. Estimates of the costs of drought to the United States alone range from $6-$8 billion annually with major droughts costing substantially more (e.g., $39B in 1988). In April 2003 the Western Governors in partnership with NOAA wrote a report, *Creating A Drought Early Warning System for the 21st Century: The National Integrated Drought Information System (NIDIS, 2004)*. The basic idea behind NIDIS is that it should take a pro-active approach to reducing or mitigating the impacts of drought. Fundamental to this objective is improved monitoring and forecasting capabilities. The specific goals of NIDIS are to:

- *Develop the leadership and partnerships to ensure successful implementation of an integrated national drought monitoring and forecasting system;*
- *Foster, and support, a research environment that focuses on impact mitigation and improved predictive capabilities;*
- *Create a drought "early warning system" capable of providing accurate, timely and integrated information on drought conditions at the relevant spatial scale to facilitate proactive decisions aimed at minimizing the economic, social, and ecosystem losses associated with drought;*
- *Provide interactive delivery systems, including an Internet portal, of easily comprehensible and standardized products (databases, forecasts, geospatial products, maps, etc.); and*
- *Provide a framework for interacting with and educating those affected by drought on how and why droughts occur, and how they impact human and natural systems*

The National Oceanic and Atmospheric Administration (NOAA) has been designated the lead federal agency for coordinating the implementation of NIDIS – a task that involves coordination among all of the relevant federal and non-federal partners, scientists, water users and policy-makers. In that regard, a key recommendation of NIDIS is that it must "*facilitate the coordination and program delivery across interagency, intergovernmental and private sector science and research programs by establishing an integrated federal drought research program.* " Specific recommendations include:

1. *Improving capabilities to monitor, understand and forecast droughts.*
2. *Encouraging all relevant federal agencies, in cooperation with the NIDIS Implementation Team, to expand their drought research portfolios by undertaking an analysis of existing research and identifying gaps. The findings of this gap analysis should guide funding and priorities for future drought research.*
3. *The federal agencies participating in the coordinated research program under NIDIS should commit a percentage (no less than five percent) of their research budgets to drought issues.*

NOAA is now in the early stages of developing an implementation plan. NASA, in coordination with NOAA, is also engaged in planning for NIDIS as part of an overall strategy to implement key aspects of the international Global Earth Observation System of Systems (GEOSS) strategic plans. In fact, the U.S. integrated Earth Observing System Strategic Plan (IEOS, 2005), as this nations contribution to the GEOSS 10-Year Implementation Plan, has embraced NIDIS as one of 6 high priority Near Term Opportunities (NTOs).

It is during this early planning phase for NIDIS that both NOAA and NASA are looking to the research community for specific guidance on research priorities for improving drought prediction and monitoring tools.

The planning for this workshop originated as a grass roots effort to bring together researchers and members of the applications communities to help determine what is needed to accelerate progress on drought prediction. The timing of the workshop was largely a reflection of recent successes in improving our understanding of the causes of long-term drought and as such was aimed at building on this momentum to help foster drought research and ensure that the research addressed the most pressing needs of the various applications communities. While not specifically geared to NIDIS planning, the workshop has set goals that very much coincide with those of NIDIS, and the recommendations coming out of this workshop should help the agencies needs for guidance. With this in mind, support for the workshop was kindly provided by the NASA programs on Modeling, Analysis and Prediction, and Terrestrial Hydrology, and NOAA's Climate Prediction Program for the Americas.

The specific objectives of the workshop were to:

1. Review drought prediction and monitoring needs for water management and agricultural applications;
2. Assess the current understanding of drought predictability and status of drought prediction efforts;
3. Identify key model uncertainties that need to be reduced in order to accelerate progress on drought simulation and prediction;
4. Develop a prioritized list of observations that are critical for drought monitoring and model initialization, validation and development
5. Develop a plan for model experimentation in coordination with the drought monitoring and applications communities.

This workshop, by bringing together researchers and members of the applications communities, takes an important step in meeting the NIDIS goals by developing the research priorities for improving drought prediction and monitoring.

In the following, we summarize the basic findings of the workshop (section II), and list our recommendations to the agencies (section III). Section IV is a summary of the workshop proceedings. Section V provides the agenda, and section VI has the list of attendees.

II. Workshop Findings

Drought is a natural disaster that, within the United States, is dealt with through crisis management at a cost to the U.S. Treasury of tens of billions of dollars. A key message that came out of the workshop was:

With increasing vulnerability to drought, a shift is needed to a risk-based approach aimed at better monitoring, early warning and prediction of drought. A risk-based approach will encourage wiser stewardship of our agricultural lands, forests and water resources.

Progress towards a risk-based approach will require improved coordination between the climate research and applications communities as well as prioritizing research that is most likely to improve risk management. Results presented at the workshop indicate that a shift to risk management based on climate prediction is now feasible because climate research has advanced to the point that 1) probabilistic forecasts of precipitation and soil moisture can be performed on the seasonal to interannual timescale, 2) the causes of multiyear droughts are being unraveled and 3) since, this work has shown that tropical SSTs are important for forcing the circulation anomalies that create drought, there is real hope that drought conditions (potentials) can be predicted (nowcasted) with useful lead times on interannual and longer timescales.

Drought monitoring and early warning:

Currently the online U.S. and North American Drought Monitors are the main vehicles for communicating to users the past and current status of drought. These have been successful and popular, partly because of their simplicity, but could be improved by becoming more quantitative and through expansion into presentation of different maps for agricultural and hydrological drought, specialized maps for different users, incorporation of future soil moisture measurements etc. Going beyond the Drought Monitors to the establishment of a drought early warning system will require soil moisture estimates either from direct measurements or from land data assimilation systems (LDAS). LDAS is currently in an experimental stage and efforts must be accelerated to develop accurate systems that have also been validated against historical records. Drought monitoring is currently constrained by a lack of high spatial resolution soil moisture measurements, while satellite data is of insufficient vertical depth, and poor knowledge of the snowpack whose spring melting provides for summer water supply. Further, monitoring drought needs to be integrated with real-time attribution studies that can assess the causes of a drought and the probability of its continuation or termination.

Drought prediction:

Modeling work has now attributed the major North American droughts of the last century and a half to global circulation anomalies forced by tropical SSTs, with the tropical oceans playing an important, and probably dominant, role. On the seasonal and longer timescale successful drought prediction will require several steps: 1) a successful SST prediction, 2) a successful simulation of the global circulation response to the SST anomalies and 3) a proper accounting of the land-atmosphere interaction that converts a precipitation anomaly into a meteorological or hydrological drought. Current climate prediction capacities are limited to those associated with ENSO, a capacity developed two decades ago. Now there is a need for efforts to examine the predictability beyond the interannual timescale and other ocean basins. In this regard it is important to realize that, for the multiyear droughts, the observed precipitation reduction averaged over the drought can be simulated by climate models forced by only the small change in mean SSTs during the drought interval (e.g. the 1930s) and that knowledge of the detailed ENSO variability and variance that make up a drought period is not required. Such forecasts, if successful, could be used to, for example, assess the likelihood of a drought persisting over the next few years as a result of a persisting La Nina-like state.

Drought prediction – or drought hindcasts – require land-atmosphere reanalyses against which forecasts and hindcasts can be validated. Significant errors persist in the atmospheric moisture budgets of the current atmospheric Reanalyses that make them of limited use for the task of validating hindcasts. It needs to be determined where the problems lie and whether improved models, improved observations or improved data assimilation are the answer.

Climate prediction models have their most skill at large spatial and temporal scales. It needs to be determined what information users need. If models used in crop and water management need information on not just long term and large scale means but also on weather variability and extreme events then it needs to be determined if prediction models can provide this information or if downscaling methods can fill the gaps.

Improving the past record of drought and the future of drought in a changing climate

As we move in to the current century we will be dealing with a climate increasingly influenced by man. On timescales of years to decades climate forcing scenarios will be used to project future climate using coupled models. For those projections to be trusted long integrations of the unforced coupled models need to be examined to see if they produce droughts akin to those observed. Future projections of hydroclimate need to be examined in the light of this and of the changes in the accompanying global atmosphere-ocean state as a means to assigning confidence levels on the projections. A better understanding of forced changes in hydroclimate will be aided by a better knowledge of past changes. Tree ring records of an even more arid climate than current that prevailed in the West for centuries during the Medieval period have raised considerable interest among users concerned by the likelihood of a man-induced return to such levels of aridity that would threaten much water use in the region.

User needs:

As a drought prediction program gets underway it is important to develop a good understanding of the needs of potential users of forecasts. What are the desired spatial and temporal scales? What are the key quantities of interest? How do needs differ by region and application? The range of users is large including agriculture, energy production, transportation, tourism, forest and wildland management, urban water districts and health care. Systems need to be developed to specialize forecasts to the needs of these users. For example climate model forecast information could be integrated with high resolution remote sensing and soil information as input to crop models and used to guide assessment of the feasibility of crop production.   Forecasts must be provided to users together with estimates of their uncertainty. Users need to know how uncertainties in forecast precipitation and temperature propagate into uncertainties in the quantities they need to know – soil moisture, stream flow, reservoir levels, ground water and snowpack.

Determination of drought costs and forecast value

Although drought costs the U.S. government tens of billions of dollars a year (during a drought) there is no systematic effort to determine drought impacts. Ways need to be developed that measure the different impacts, including both primary and secondary impacts. This is required as a precursor to measuring the value of forecasts.   Forecasts can be considered to be of value if their use leads to less government costs as well as less losses to water users, less social disruption, equity of access to water, and protection of new users.

To facilitate drought-related decision-making scientists and users need to begin using a common language and tools that relate historical data and forecasts to a water manager's perspective. Managers also need tools with which to present climate information to stakeholders. This will best be accomplished through interactions that are maintained over time whereby scientists are involved in the drought planning process and water managers in the climate research and prediction process. It is important to have forums that will bring the different communities together to develop communication and to bring perspectives together.

III. Workshop Recommendations

In this section we present our recommendations for research, observations, and programmatic initiatives to accelerate progress on the drought prediction problem and enhance our drought monitoring and early warning capabilities. The recommendations are organized into requirements for 1) subseasonal to interannual drought prediction, 2) decadal and longer drought prediction, and 3) our utilization of drought prediction information.

Overarching Recommendation

An interagency (NASA, NOAA, NSF, DOE) drought research program should be initiated that would focus ongoing and new drought-related research on the definition, predictability, and prediction of drought, and on the utilization of this information by stakeholders.

It is further recommended that the program be established within the next 1-3 years as a central part of the agencies planning activities for NIDIS. The program would consist of three elements:

- **SHORT-TERM DROUGHT PROBLEM:** improved definition, attribution and prediction on sub-seasonal to interannual time scales.

  Action: Form a national consortium of prediction centers and drought researchers that would use existing tools/models and observing systems (monitoring) to assess the quality of monthly to interannual forecasts of precipitation and other hydrological quantities. This consortium would also investigate the impact of new observations and the utility of new forecasting techniques (such as multi-model ensembles), perform observing system sensitivity studies related to hydrological variables, and make recommendations for the improvement of observing systems and modeling/assimilation systems.

- **LONG-TERM DROUGHT PROBLEM:** improved understanding of the mechanisms of decadal drought and its predictability, including the impacts of SST variability, deep soil moisture variability, and the impact of global warming.

  Action: Consolidate multi-agency research efforts into a program that will address the mechanisms that control the land surface branch of the hydrological cycle at decadal timescales. The program would include basic research on the causes of historical droughts and would assess the usefulness of coupled climate models for drought-related diagnostic and predictability studies. The program would also support the use of paleodata for improved estimates of current drought risk and would assess potential effects and implications of long-term drought predictions for policy/planning/etc.

■ **UTILIZATION OF DROUGHT PREDICTIONS:** Transition of improved monitoring/prediction/attribution tools to operations; a bridging of the gap between hydrological forecasts and stakeholders (utilization of probabilistic forecasts, education, forecast interpretation for different sectors, assessment of uncertainties for different sectors, etc.).

Action: Provide a focal point among agencies with drought research interests that will facilitate transition of research advances into operations. It should support interaction with the user community (e.g., NIDIS) to define aspects of drought that are most useful to predict and improve how drought information is conveyed, and it should foster collaboration/ coordination with neighboring countries (e.g., the new Canadian Drought Research Initiative).

Specific Needs:

Progress on the overall drought problem will require tight coordination and strong support for all three thrusts. Within each thrust we have, however, attempted to prioritize the research, modeling, observational and other needs (with highest priority items list first).

1. THE SHORT-TERM DROUGHT PROBLEM

<u>Develop coordinated effort in drought monitoring, prediction and early warning, in support of NIDIS</u>:

- Creation of a "National Drought Attribution and Prediction Consortium" (see Appendix) that uses multiple models and analysis techniques to address drought problems in coordination with stakeholders (as outlined in 3 below)

<u>Establish long (multi-decade) climate records adequate for retrospective studies, and as required for initialization, calibration and validation:</u>

- global and regional atmosphere/land reanalyses, with a focus on the improved representation of the hydrological cycle

<u>Improve (real-time) observation/assimilation of key surface variables needed for monitoring, model initialization and/or validation (with uncertainty estimates):</u>

- soil moisture profiles (monitoring system focused on "sensitive" regions, such as a pilot effort focused on the Great Plains)
- snowpack
- forcing data (precipitation, radiation, etc.) for land data assimilation
- vegetation properties (e.g., from NDVI, EDVI MODIS data)
- surface temperature
- streamflow

<u>Improve coupled (atmosphere-ocean-land) model prediction system. Development should focus on:</u>

- teleconnections between SST variations and continental precipitation
- weather statistics (particularly extreme events)
- land/atmosphere interaction
- surface/subsurface water reservoirs (including estimates of recovery time)

Improve understanding of roles of local and remote processes on drought variability and predictability, as a function of timescale:

- role/predictability of drought-related SST variations (including ENSO)
- role/predictability of subsurface land water
- role/predictability of short-term atmospheric variability (e.g., weather, MJO)

2. THE LONG-TERM DROUGHT PROBLEM

Foster research into the mechanisms that control the land surface branch of the hydrological cycle at multi-year (decadal) timescales:

- decadal ocean variability in the context of regional drought
- connection of ENSO and other shorter-term SST variability to the initiation and demise of long-term drought
- deep soil moisture variability (drought unforced by SSTs)
- aerosol feedbacks (i.e., the Dust Bowl)
- decadal vegetation feedback
- global change
- drought migration

A research effort focusing on the causes of historical droughts (attribution studies):

- multiyear-to-decadal hindcasts of past droughts
- characterization of drought duration, seasonality and spatial extent
- development and improved use of paleodata for estimating decadal and longer term drought variations, including mega-droughts

Improve simulations of hydrological variability on decadal time scales. Development should focus on:

- realistic decadal SST variability and teleconnections to regional drought
- realistic simulation of subsurface water on decadal time scales

Foster research focusing on the predictability of multiyear-to-decadal drought:

- assess the predictability of SST variability related to long term droughts
- assess the predictability of the onset and demise of long term drought
- experimental forecasting of droughts on the multiyear timescale

3. UTILIZING AND CONVEYING DROUGHT INFORMATION

Coordinate the development of new drought indices to link assessment, monitoring and prediction efforts:

- work with stakeholders and the Drought Monitor community to develop objective indices useful for validation of drought predictions
- facilitate the incorporation of new land surface monitoring tools (outlined under Short Term Drought needs) into new drought indices

Improvements in the conveyance of drought predictions to stakeholders:

- improved definition(s) of the onset and demise of drought

- development of more objective and applications-specific drought indicators
- improved predictions of variables (beyond basic hydroclimatic variables) that are directly linked to user needs: e.g., vegetation stress, quantities affecting rangeland and forest health), dust transport, etc.
- work with stakeholders to revise traditional drought response strategies, taking into account the probabilistic nature of forecasts.

Interagency support for the transfer of research results into operations (e.g., collaboration in efforts such as the NOAA Climate Testbed).

Improved collaboration/coordination with neighboring countries (e.g., the new Canadian Drought Research Initiative).

IV. Workshop Proceedings

Tuesday AM
The morning session consisted of the following invited talks:

1. *NIDIS planning at NOAA* (Chet Koblinsky)
Chet outlined NOAA's role as the lead agency for coordinating the implementation of NIDIS. In anticipation of congressional authorization of NIDIS, NOAA is tasked to establish immediately a broad-based Implementation Team to carry out those aspects of NIDIS that can be accomplished through existing authorities and resources. This effort is being led by Robert Livezey. NOAA is developing a plan and identifying resources for management of the Team starting in FY06, a plan that will include the establishment of an interagency office. The current FY06 budget supports COOP modernization, the Water Resources initiative, and ongoing climate research**.** Planning for FY07 includes data integration, development of assessment tools, and outreach and educational activities. Planning for FY08 is focused on addressing major gaps in drought prediction research and on the Integrated Surface Observing System. The relevant website is: **http://www.nws.noaa.gov/ost/climate/NIDIS/** . Chet emphasized that what was needed from this workshop is a better understanding of research needs to improve prediction. He also emphasized the need to prioritize and to decide on time frames as to what needs to be done first, because resources are tight.

2. *NIDIS planning at NASA* (Jared Entin)
Jared reviewed the recent Integrated Earth Observing System (IEOS) public engagement workshop where the selection of NIDIS as a Near Term Opportunity (NTO) for IEOS was discussed. The various agency contributions were outlined, including NASA's role in developing observing systems, datasets and modeling systems. Relevant NASA satellite missions include GRACE (for ground water) and the future missions Aquarius (for sea surface salinity, or SSS) and Hydros (for soil moisture monitoring and model initialization). Relevant NASA modeling activities lie at the GMAO and GISS, including projects funded under the new NASA MAP and NEWS research announcements. Also relevant are the more applied projects from the CAN and NEWS NRAs that link NASA data products (observations and modeling information) to decision makers. Jared noted that both NASA and NOAA have decision support tools, which suggests several questions. How are these used and where? Are these what decision makers want? Where are they lacking? Do we need, for example, soil moisture and snowpack information at higher resolution, etc.? The workshop should guide NASA about where to put resources. Satellites are expensive but can be very useful.

3. *Moving from Crisis Response to Drought Risk Management: Shifting the Paradigm* (Don Wilhite)
In his talk, Don emphasized the need to understand what the clientele needs. Agricultural drought, hydrological drought, and socio-economic drought relate to insufficient water to meet human demands. Agricultural drought is focused on soil moisture, while hydrological drought occurs on longer timescales as groundwater is affected. Social and economic impacts are associated with both agricultural and hydrological drought. On longer timescales, there is increased emphasis on water resource management.

Conflicts between water users (those associated with agriculture, energy, transportation, tourism, recreation, fires, urban water supply, and human health) are increasing. Increasing impacts and an expanding clientele combine to increase vulnerability to drought. The vulnerability is growing nationally, including in the eastern United States. The Pacific Northwest has now been in drought for 6 years, with impacts on drinking water, hydropower, tourism, agriculture, shipping, nuclear power (water return flow), wildfire, and endangered species.

Unlike many other natural hazards, drought is a creeping, slow-onset phenomenon. There is no universal definition, but it is clear that definitions need to be region- and application-specific. Drought is best described through multiple indicators and indices. The lack of clear definitions often causes confusion and inaction by policy makers.

Drought is the most costly US disaster, but there is no systematic effort to determine impacts. In 1995, FEMA estimated that drought costs the nation $6-8 billion a year. The 2002 estimate (produced by 10 states) was $20 billion using different methods, and not all sectors were covered. Congress has appropriated $30B in drought relief since 1988. Federal assistance programs are many, but they are poorly coordinated and reactive. In fact, such relief can increase vulnerability – there is no incentive to change the way things are done if the federal government pays out. Risk management can improve the ability to make decisions. (The Australians provide an example.) Reducing drought vulnerability requires preparedness and mitigation; a good drought damage mitigation plan involves monitoring, early warning, and prediction, as well as risk and impact assessment. By focusing on preparedness and mitigation, we move from crisis management to risk management. Currently 38 states have drought plans.

The basic conclusion is that crisis management is ineffective and does not produce wise stewardship. With increasing vulnerability, we need to shift to a risk-based approach aimed at better monitoring, prediction and planning. Can scientists deliver? How do we support such a paradigm shift? One possibility is to shift resources in agencies from reactive programs to mitigation programs. NIDIS suggests that 5% of Federal competitive research should be designated for drought-related research.

The National Drought Preparedness Act, which was reintroduced into Congress in 2005, creates the National Drought Council, with the USDA as the lead agency. The goal is to develop a National Drought Policy.

4. *Drought monitoring and prediction: challenges and opportunities.* (Doug LeComte)
NOAA/CPC and NCDC, USDA, and the NDMC, with contributions from numerous federal and non-federal agencies, have produced a composite drought map - the Drought Monitor - each week since 1999. Inputs to the drought monitor include streamflow, SNOTEL observations, soil wetness from a soil model, vegetation health, soil ratings, and various other drought indicator blends. Limitations of the current Drought Monitor include a subjective interpretation of indicators, a lack of soil moisture measurements (much needed), and attempts to portray hydrological and agricultural droughts on a single map. The Drought Monitor could be improved, for example, by using land data assimilation for better soil moisture monitoring, expanding soil moisture networks, improving the interpretation of remotely sensed data (NDVI and EVI, MODIS), and improving the composite drought indicators (e.g. basin water index).

The NOAA Climate Prediction Center produces a Drought Outlook one season in advance. The input to the Drought Outlook includes the NCEP forecast suite up to a seasonal forecast, climatological information, 2 week soil moisture forecasts, and constructed analogues. Drought forecasting capabilities are limited because the forecasts are combined subjectively and because seasonal precipitation forecasts are poor – especially during the warm season. There is a need to provide more quantitative probabilistic forecasts.

To improve drought forecasting, we should improve the seasonal forecasting of precipitation (through improved dynamical models), improve soil moisture fields via a land data assimilation system (LDAS), and provide observations to benefit the simulation of air-ground interactions in seasonal models. We need to improve our understanding of ocean-atmosphere interactions, and we need to understand the sources of decadal changes. We should link LDAS soil moisture with medium- and long-range ensemble models to produce probabilistic forecasts. We need to both establish priorities for research and observations and establish a timeline for improving drought prediction.

5. *Drought and Agriculture in a Decision Framework: Examples from South America* (Walter Baethgen and Chet Ropelewski, given by Ropelewski)

Chet emphasized that different types of decisions are made at different time scales. For example, on the time scale of days, decisions are made regarding when to apply herbicide or pesticide. On monthly to seasonal time scales, the concerns are about planning annual crops and irrigation needs, while on time scales of a few years, decisions are made about crop and pasture rotation.

In terms of general principles, it is important to know what factors influence decisions. How important is climate information? One needs to understand the system: processes and interactions, bottlenecks, flexibility to make changes, etc. It is important to involve users from the start (e.g., government, insurance, credit, agribusiness, farmers, advisors). We need to learn from the past, monitor the present, and provide probabilistic forecasts for the future.

The needed information depends also on spatial scale. At the national scale, important products include effective rainfall, remotely sensed vegetation status, model evapotranspiration, and soil maps – all of these are used for soil water balance assessments. At the regional scale, remote sensing (Landsat 7: “where are the wheat fields?”), soil maps, and weather records are used to assess the feasibility of wheat production via crop models. Farm income from wheat production in Uruguay – according to a model – improves when going from rain-fed wheat to irrigated wheat. There is a strong relationship between El Nino and wheat yield in Uruguay, since El Nino produces wet conditions there. Challenges for drought prediction in the context of agriculture include: (a) the need to consider factors other than climate, (b) the low skill of climate forecasts, (c) the need to improve interactions with technology (e.g. irrigation), and (d) unrealistic user expectations.

In summary, we need to be aware of the breadth and limitations of the factors affecting drought and agriculture, to encourage flexibility in decision making, and to be aware of useful alternatives (e.g., irrigation) to climate information.

6. *Water resources and drought: critical information needs* (Andrea Ray/Roger Pulwarty; given by Andrea Ray)

Andrea discussed the need to facilitate drought response by reducing and managing uncertainty and by evaluating the effects of climate conditions and the value of forecasts. Uncertainty can be technical (e.g., in prediction skill), institutional/legal, or behavioral/organizational. The value of forecasts can be judged in terms of management tradeoffs, typical benchmarks (idealized expected value), or through other measures, such as the mitigation of societal disruption, equity of access to water, or the protection of new uses. The potential users include municipal/residential/industrial/recreational users, agricultural users, government managers, regulators, policy makers, planners, scientists and engineers, and NGOs (e.g. biodiversity interests).

The users want information, for example, on soil moisture, stream flow, reservoir levels, ground water, and snowpack. They need to know how precipitation and temperature forecasts relate to these quantities. There are more and more requests for information on interannual to decadal timescales, e.g., for reservoir inflows. Can we provide reliable baseline information on these time scales for planning? Are the baselines still valid under projections of varying and changing climates?

The framework for drought related decision-making consists of problem identification (drought itself is not the issue but how it relates to other problems, risk perception), problem formulation, decision-making (e.g., management options for Lake Powell), implementation, and evaluation of outcomes. The issues for droughts in the western U.S. include property rights (including water), Native American water rights, urbanization and population growth, water quality, and groundwater overdraft.

Andrea outlined some of the Regional Integrated Science & Assessment (RISA) experiences, as well as the activities of the Western Water Assessment (WWA) and CDC. This included information on decision studies of water management and agriculture and on key institutions in drought policy and decision-making on national, regional, state, and local/municipal scales.

CLIMAS experience with users as part of the Arizona drought task force included participation in the creation of a State Plan and the outlining of challenges for improving the Drought Monitor (accounting for diverse topography, monitoring multiple sources of surface water, gaps in the monitoring network, multiple scales that might affect adjacent areas in different ways). The California Assessment Project (CAP) experience with users included providing information on climate change and long term water planning. Some of the key information galvanized interest from state legislature (e.g., on snowpack change).

The users' ability to assess drought-related problems is an issue. The information available to assess conditions is not all in one place but is spread across the websites of many agencies. Researchers and water managers have very different perspectives and goals with respect to drought.

To facilitate drought-related decision-making, scientists need to collaborate with sophisticated, but non-climate, experts in a common language. The information must be flexible in its format, area, and time scale. Tools are needed to relate observations, historical data, and forecasts to water managers' perspectives and to evaluate climate scenarios in management scenarios. Managers need to know how to talk to their stakeholders. We need benchmarks beyond "idealized value". We need to form partnerships with interactions that are maintained over time, where scientists influence the drought planning process and water managers influence science, where the interaction leads to innovation in both science and management, and where fora allow communication, learning, and bringing perspectives together.

Follow-up discussion centered on how to move from research to operations – what is the process? The new NOAA Climate Test Bed was cited as an example. It was also mentioned that we need longer records (for example, from LDAS or reanalyses), but there are issues of calibration. Other issues concerned the need for attribution studies, for analogues, and for defining triggers.

The morning invited talks were followed by a general discussion session. The following points were raised by various workshop participants during that discussion.

-- Better soil moisture information is needed. LDAS information can be difficult to obtain, despite the fact that LDAS has been around for several years. LDAS delays result from the fact that when NCEP ran 4 LDAS land models, it was found that each of the 4 models had errors. It was decided to pause to allow each group to solve their primary systematic errors.

-- When does something go from research to operations? What process is used to make this transition? The concept behind the climate test bed (CTB) facility was mentioned as a way to accelerate movement of research into NOAA forecasts.

-- There is a need to validate LDAS with historical records. We need longer LDAS records. We can potentially use global retrospective integrations (reanalyses). Regional reanalyses are shorter but provide better resolution. The minimum resolution is 1/8 deg with 32km forcing from regional reanalysis.

-- Analogues could be used for forecasting, but this necessitates a clear understanding of past droughts, highlighting the need for attribution studies.

-- Are there common deficiencies in land models? Is there, for example, a longer-term memory in the land – e.g., longer than a season – that is not included in current land models? Land surface model inter-comparison studies would not reveal such a common bias.

-- Drought can only be solved through interdisciplinary research. Some things to consider: policy triggers may exist even though drought evolves gradually. Demand increases over time even in a stationary climate or population. Managers often talk about droughts in years even though they are decadal in nature. Basin planning is not done on decadal timescales. Are groups working on efficiency of water use and wastage? Many cities have conservation measures in place, not so true in agriculture.

-- In the western US, we do not have good estimates of snowpack (in water equivalent) or soil moisture, causing errors in forecast inflows. To correct this, we should look first to remote sensing data, since in situ measurements are costly. Also, we need to improve model-assimilated products. Other needs include: forecasts of onsets and demise of drought, guidance on how to convey information/uncertainty, estimates of the value of forecasts (e.g. drought prediction leads to better reservoir management but there will be losses anyway -- how much?), and evaluations of the impact of forecasts. Idealized potential losses must be considered, which is a problem. New tools are required to (for example) record impacts and determine losses. We need to validate the forecasts. There is a demand for past data reconstructions, especially information on long droughts in last millennium. Such reconstructions could influence decision makers; paleodata in this context is very valuable.

-- We need to identify the stakeholders. What are the relevant time scales, quantities, resolution, and geographical differences? We need to consider how to use in situ vs. remotely sensed data. What is envisioned for an early warning system?

Poster Session

The following are brief summaries of the posters presented during the poster session.

Barrie Bonsal and Elaine Wheaton- "Atmospheric Circulation Comparisons Between the 2001 & 2002 and 1961 & 1988 Canadian Prairie Droughts"

The 2001 and 2002 Canadian Prairie droughts were unusual climatological events in terms of their extreme precipitation anomalies and extraordinary persistence. Over the west-central Prairie Provinces, well below normal precipitation was recorded for a remarkable eight consecutive seasons from autumn 2000 through summer 2002. Analysis of the mid-tropospheric circulation during these droughts indicates that the patterns were markedly different from those associated with the severe, multi-season Prairie droughts of 1961 and 1988. In particular, the circulation during 2001 and 2002 lacked the distinct meridional flow over the North Pacific and North America that has been associated with previous dry periods over western Canada. Moreover, the evolution and persistence of the 2001-2002 droughts have no clear relationships with large-scale teleconnection patterns that have influenced past climate extremes over western regions of the country. Results suggest that the recent droughts may be related to a northward extension of persistent drought producing circulation anomalies that impacted the continental United States. These differences in circulation indicate that further research is required to better understand and aid in the prediction of extended dry periods over North America.

Ken Snelgrove, S. Yirdaw-Zeleke, E.D. Soulis, F.R. Seglenieks – "GRACE (Gravity Recovery and Climate Experiment) Measurements for Drought Monitoring?"

In 2002, the GRACE (Gravity Recovery And Climate Experiment Mission) satellite platform was launched to measure, among other things, the gravitational field of the earth. Over its five year life a pair of orbiting satellites will produce a time series of mass changes of the earth-atmosphere system. When integrated over a number of years, this will yield a highly refined picture of the earth's gravity. However, month to month changes in mass is an indicator of the integrated value of watershed moisture storage. It has been reported by Wahr et al. (2004) that when smoothed over 1000 km that centimeter accuracy can be achieved in monthly storage change. The goal of this research to compare changes in moisture storage over western Canada using GRACE data with those developed by atmospheric and hydrologic water balances techniques. This work builds on a previous study undertaken as part of MAGS and will highlight the recent drought in western Canada as a precursor to the proposed Drought Research Initiative (Canada DRI). Monthly estimates of watershed storage have been developed for the Mackenzie River basin.

Celine Herweijer, Richard Seager and Edward R. Cook, "North American Droughts of the mid-late 19th Century: a history, simulation & implications for Medieval drought"

Historical accounts, early instrumental data, and a network of gridded tree-ring data have been used to identify three major multi-year droughts during the mid-late 19th century: 1856 - 1865, 1870 - 1877 and 1890 - 1896. Each coincided with the existence of anomalously cool tropical Pacific SSTs. To examine the physical mechanisms behind these droughts two ensembles of simulations with an atmosphere general circulation model (AGCM) were generated: the first forces an AGCM with the observed history of SSTs everywhere from 1856 to 2001 (the GOGA experiment), the second forces the AGCM only with tropical Pacific SSTs, being coupled to a two-layer entraining mixed layer (ML) ocean elsewhere (the POGA-ML experiment). A comparison of modeled soil moisture with tree-ring reconstructions of the Palmer Drought Severity Index (PDSI), a proxy for soil moisture, from the North American Drought Atlas is made. Both the GOGA and the POGA-ML models do an impressive job at capturing these droughts, and the wetter spells in between. As for the results of Schubert et al. (2004) and Seager et al. (2005), the implication is that these widespread and persistent droughts are SST forced, primarily from the tropical Pacific. Using coral data for the last 1000yrs to reconstruct a NINO 3.4 history, we apply the modern day relationship between NINO 3.4 and North American drought to recreate two of the severest Medieval ~Rdrought epochs~R in the western United States. The large-scale spatial similarity to the Drought Atlas data demonstrates the potential link between a colder eastern equatorial Pacific and the persistent North American droughts of the Medieval period.

Phil Pegion, Siegfried Schubert, Max Suarez, and Randy Koster- "On the Nature of the Recent SW US drought"

The recent drought in the Southwestern US have been ongoing since the end of the 1997/1998 El Nino. The NSIPP-1 AGCM captures this drought, but fails to persist the drought into 2002, which was the driest year in nature. It is during the winter of 2001/2002 where the model runs break the drought. Some ensemble members of high resolution simulations do manage to produce a drought in the winter, and it appears to be linked to variability of precipitation in the tropical Pacific ocean.

D. Legler and C. Stephens – "U.S. CLIVAR - The US Contribution to the Program on Climate Variaiblity and Predictability"

The US has a significant set of CLIVAR activities that address the current US CLIVAR objectives:

* identify and understand the major patterns of climate variability on seasonal and longer time scales and evaluate their predictability;
* expand our capacity to predict short-term (seasonal to interannual) climate variability and search for ways to predict decadal variability;
* better document the record of rapid climate changes in the past, as well as the mechanisms for these events, and evaluate the potential for abrupt climate changes in the future;
* evaluate and enhance the reliability of models used to project climate change resulting from human activity, including anthropogenic changes in atmospheric composition; and
* detect and describe any global climate changes that may occur.

This poster describes the programmatic implementation strategy of U.S. CLIVAR, its range of activities, and how it is coordinated.

Robert S. Webb (NOAA-OAR Climate Diagnostics Center, Boulder, CO), Connie Woodhouse (NOAA-NESDIS-NCDC Paleoclimatology Branch, Boulder, CO), Gregg Garfin (University of Arizona-ISPE-CLIMAS, Tucson, AZ) – "Developing Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin".

The recent drought and associated impacts across much of the western USA has created a window of opportunity for collaborations between paleoscientists and water resource managers. In the Colorado Front Range, partnerships between scientists and several water management agencies have resulted in tree-ring based streamflow reconstruction that are now being used in planning and management. Other efforts with the Salt River Project in Arizona are also yielding productive collaborations. In early May 2005 a workshop was held to bring together paleoclimatologists, hydrologists, climate scientists, and resource managers concerned with Colorado River Basin water supplies to share lessons learned and chart a course for future collaborations. Key findings included: 1) Collaborative partnerships are key to developing and providing useful and usable information for decision support. 2) For scientists to make their data and analyses useful to water resources decision makers, they need to understand the language and vocabulary of water managers and explain how reconstructions are created, calibrated, and verified, to make the information "transparent". 3) Water resources managers can use probabilistic information, are comfortable with uncertainty, but need characterization of uncertainty. 4) Water managers are concerned about the skill of hindcast data and remain perplexed by the variety and complexity of measures of skill employed by the dendrohydrology community. 5) Tree ring reconstructions are valuable to put the instrumental record within a broader context of hydroclimatic variability and thus potentially useful decision support resources to develop scenarios for evaluating system reliability.

Justin Sheffield, Lifeng Luo and Eric F. Wood, Princeton University, Princeton, New Jersey, USA – "The development of a simulated soil moisture analysis for the US for real-time monitoring and seasonal forecasting of drought."

An experimental real time drought monitoring and seasonal forecasting system has been developed for the USA. High resolution fields of hydrologic variables are generated from land surface model simulations and are used to represent agricultural and hydrologic drought severity. The system comprises three parts: a 50-yr retrospective simulation that forms a drought climatology; a real time monitoring component that updates hydrologic fields daily; and a forecast component that currently makes seasonal forecasts on a monthly basis using ensemble (probabilistic) forecast techniques with lead times up to 9 months. The soil moisture fields from these simulations are used as an index of drought, which has been used to analyze drought variation over the past 50 years.

Tsegaye Tadesse*, Jesslyn Brown†, Michael Hayes*, Don Wilhite*, and Mark Svoboda*- "A Data Mining Approach to Monitor Vegetation Stress Due to Drought: *integrating satellite, climate, and biophysical data over the U.S. Central Plains."*
* National Drought Mitigation Center, University of Nebraska-Lincoln, NE 68583-0749
† SAIC, USGS/National Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198

A joint effort by the National Drought Mitigation Center (NDMC), the U.S. Geological Survey's National Center for Earth Resources Observation and Science (EROS) and the High Plains Regional Climate Center (HPRCC) is underway to develop and deliver timely geographic information on drought at a 1 km^2 resolution. These maps show an experimental drought indicator, the Vegetation Drought Response Index (VegDRI), developed to provide regional and sub-county scale information about drought effects on vegetation. VegDRI is calculated using data mining techniques that integrate complex information from satellite measurements, climate-based drought indices, land cover types, soil characteristics, and additional environmental factors. These VegDRI maps deliver continuous spatial coverage, and are inherently finer in spatial detail than other commonly available drought indicators such as the U.S. Drought Monitor. Further development of the VegDRI product is planned to monitor drought over the lower 48 states using these techniques.

Ian Ferguson, Philip Duffy, S. Schubert, Philip Pegion and Xu Liang – Potential Predictability of Drought in the Western U.S.

We assess the potential predictability of drought in the Western U.S. in a 14-member ensemble of 20th century climate. Simulations were performed with the NASA NSIPP-1 global atmospheric model, forced with prescribed, observed sea surface temperatures (SSTs). Ensemble members have identical SST forcing, with varying initial conditions. In general, agreement among ensemble members indicates a strong influence of SSTs, and therefore indicates potential predictability; disagreement among ensemble members indicates a strong influence of initial conditions, and therefore a lack of predictability. Previous work by Schubert et al. showed that for the Great Plains region, the ensemble-mean reproduces several major historical droughts of the 20th century, indicating that these droughts resulted in part from anomalous SSTs, and are, at least in theory, predictable. We perform a similar analysis for the Western U.S. Initial results show much poorer agreement between ensemble members. These results suggeste a stronger influence of initial conditions (i.e., chaotic variability) on precipitation variations in the Western U.S. compared to the Great Plains. Employing a simple measure of co-variability among monthly precipitation anomalies in the ensemble members, we find the greatest potential predictability in the tropical Pacific and other tropical regions, and the weakest predictability at high latitudes.

Shaleen Jain, Martin Hoerling, and Jon Eischeid, NOAA-CIRES CDC – "Decreasing Reliability and Increasing Synchroneity of Western North American Streamflow."

Assessing climate-related societal vulnerability and mitigating impacts requires timely diagnosis of the nature of regional hydrologic change. A late-twentieth-century emergent trend is discovered toward increasing year-to-year variance (decreasing reliability) of streamflow across the major river basins in western North America~W~VFraser, Columbia, Sacramento~VSan Joaquin, and Upper Colorado. Simultaneously, a disproportionate increase in the incidence of synchronous flows (simultaneous high or low flows across all four river basins) has resulted in expansive water resources stress. The observed trends have analogs in wintertime atmospheric circulation regimes and ocean temperatures, raising new questions on the detection, attribution, and projection of regional hydrologic change induced by climate. Journal of Climate: Vol. 18, No. 5, pp. 613~V618, 2005. doi: 10.1175/JCLI-3311.1

Wood, Andy W., Ali Akanda and Dennis P. Lettenmaier – "An Experimental Daily US Surface Water Monitor at the University of Washington"

In April 2005, we launched an experimental national hydrologic nowcasting system which produces a daily update of soil moisture, snow water equivalent (SWE) and runoff across the US at 1/2 degree resolution. The nowcasting system was implemented via the following (automated) sequence of steps: 1) a daily processing of meteorological data (precipitation and temperature maxima and minima) from a set of 2131 stations into a gridded 1/2 degree model forcings; 2) continous hydrologic simulation using the VIC macroscale model from 1915 to the current date; and 3) interpretation of the resulting soil moisture, SWE and runoff simulation with respect to the historical climatology of this run (hence identical methods are used for current and retrospective estimates). The meteorological data are taken from the NOAA Applied Climate Information System (ACIS), and the station list was restricted to COOP stations having both reliable real-time reporting and long term retrospective records. Gridded forcings are developed via an "index-station approach", and model forcings other than temperature and precipitation are either derived (e.g., relative humidity, solar radiation) or (in the case of average wind speed) taken from a pre-existing 1/2 degree forcing dataset (see companion poster by Andreadis et al.). VIC model parameters are based on prior modeling work in the North American Land Data Assimilation System (N-LDAS). The primary products of the system are surface maps of soil moisture, SWE and runoff, as well as their anomalies and percentiles; regional (i.e., by major river basin and/or state) water balance summary timeseries; and an online archive of monthly soil moisture, SWE and runoff maps from 1915 to the present. The use of identical real-time and retrospective methods is the chief strength of this system (and one which sets it apart from most existing real-time land surface modeling efforts), in that it eliminates methods-related bias in interpreting real-time model fields with respect to the historical climatology. This poster describes the system's initial implementation, and discusses progress toward additional diagnostic products and surface water outlooks to be initialized by this system.

Tuesday PM

The afternoon session began with a series of contributed talks on applications.

1. *Enhancing water management applications with surface observation and modeling* (Paul Houser)
This talk focused on the need to conduct research that addresses end-user needs. Three reasons for why science and technology advances don’t always lead to improvements in applications include: 1) an inadequate understanding of applications that produces non-optimal science/technology investment, 2) inadequate technology (lack of useful water resource observations), and 3) inadequate integration of information. The challenge is to improve the prediction of consequences. This can be done by defining research priorities based on needs, observing key environmental factors, integrating information from diverse sensors, assessing the current environmental conditions, predicting future environmental possibilities, and linking to decision and operation support systems. Useful predictions are the critical link to stakeholders. We must move towards a new paradigm of climate models that produce useful weather-scale, process-scale, and application-scale prediction of local extremes (not just mean states). We must also more fully constrain climate models with observations.

2. *The search for improved drought monitoring tools, issues and applications in Canada*. (Ted Obrien with Aston Chipanshi)
Drought is very costly and affects all sectors. The worst droughts have cost the Canadian economy $5 Billion per year. One of the worst drought years on record for Canada was 2001. In some regions the drought has persisted for over four years. Information development and distribution, contingency plans, long-term safety nets, and water development are key to mitigating drought. Research, technology transfer and producer adaptability are all reducing the effects of drought.

According to its terms of reference, the Agriculture and Agri-food Canada Online (AAFC) Drought Committee serves several purposes, including: (a) representing all agricultural regions of Canada, (b) reporting on national drought conditions to the federal Minister of AAFC, (c) identifying existing and/or potential drought response mechanisms, strategies, and information gaps, (d) identifying and recommending actions to address and mitigate drought pressures, (e) prioritizing and recommending future action and resource allocations that can be used to help producers adapt to drought, and (f) ensuring AAFC’s approach to drought is coordinated with other drought-related committees and initiatives. Industry is monitored in priority areas on a bi-weekly basis through climate indicators, livestock marketing, regional crop reports, pasture grass conditions and forage supply, water supply and quality, provincial government responses, and other indicators.

A relevant USA and Canada Agreement is in place to foster cooperation. Specifically, "the Parties will develop datasets and mechanisms for the collection and dissemination of near real-time data and historical records that will facilitate improved understanding of the variability and change in climate and weather extremes." The North American Drought Monitor (apparently an example of such cooperation) includes Canada, the United States and Mexico. Ted noted that there is no national (Canadian) drought policy. There are very few stations in Canada. Most have fewer than 40 years of data, making drought classification difficult. There is a need for greater station density for precipitation. Satellite- based soil moisture estimates tend to have problems with ice in Canada.

3. *Drought and Wildland Fire Management* (Tim Brown)
About $10B is spent each year on fire suppression and treatment. We need to know how drought impacts the different fuels (fuel response time, memory, impact threshold indices). Strategic decisions require information on where to put resources, timing (when to be successful), and funding requests. The impact on treatment success depends on whether drought will promote species or cause mortality, and whether objectives can be satisfactorily met. Information is required on various time scales (short-term, seasonal, interannual, and decadal). While prediction is performed at coarse resolution, monitoring must occur at high resolution (e.g., 30 m).

There are various efforts to couple physical models to dynamic vegetation models. International multi-data proxies include fire data sets; we need to find out how to make the data more useful. Quantities needed include temperature, humidity, and precipitation.

4. *The Application of Climate Information and Modelling in Monitoring Drought and Risk of Land Degradation in Queenslan*d (Jozef Syktus).
About 80% of Queensland is grazed, generating about $3.3B. ENSO exerts a large impact, but decadal time scales are also important (PDO). To manage the risk of grazing land degradation, we need numerous things, including: (a) an objective assessment of resource conditions, (b) an understanding of socio-economic and climate drivers of degradation and recovery, (c) objective estimates of 'safe' livestock carrying capacity, (d) forecasting systems based on our understanding of climate drivers and key management decisions for graziers, (e) climate change and drought research, and (f) an understanding of the impact of land degradation on natural resource base, productivity and coastal water quality (Great Barrier Reef).

At least eight major degradation episodes have occurred. We have advanced our understanding of how climate, economics and stock numbers interact to cause degradation, and the knowledge is communicated to users. CINRS is developing the capacity to monitor and produce probabilistic forecasts of drought and degradation risk. One emerging issue is the impact on rural and urban water supplies of the persisting drought in eastern Australia during the past decade, which may be related to stratospheric ozone depletion and CO2 increase. Someone asked if there could be a feedback between degradation and subsequent drought. The answer is yes, but the interpretation of relevant model results is limited by model resolution.

5. *Estimating the economic impacts of drought* (Roger Pulwarty, with Mike Hayes and Charles Howe)
Assessments of the economic impacts of drought, though attainable, have received too little attention to date. Assessments are difficult because (for example) droughts are slow in their onset and impacts vary with location and spatial scale. Impacts are both direct and indirect, and the secondary impacts may be larger than for other climatic extremes. Over larger regions (e.g., across the nation), drought impacts average out over 'winners' and 'losers' due to local impacts, mitigation practices and markets. Some impacts may be counted twice due to the widespread nature of drought and the fact that it affects more than one industry. Cumulative impacts of drought may extend beyond the period of its climatological duration or over multiple seasons, especially in local areas. Assessing the role of relief payments or reserve funds is difficult. There is no central clearinghouse for impacts data concerning drought.

Past and present estimates of the economic impact of drought may be significantly lower or higher than reported. Due to the lack of detailed data on losses from drought, weighing monitoring costs against the potential savings from better data and forecasts is difficult. We need to use idealized benchmarks of economic value. Future drought management efforts, and climate impacts assessments in general, should recognize: (a) the unique nature of drought, along with its natural and social dimensions, (b) the difficulties of developing effective cost estimates of impacts as needed for calculating rates of return, (c) the contribution of research, monitoring, and development to loss reduction, and (d) the need to evaluate strategies for reducing avoidable losses.

Discussion following the talk addressed the role of research in reducing drought costs. The first step is determining what the costs are. There may be a benefit to studying drought in the context of climate variability in general, but it is probably advantageous to focus on getting "one thing right", namely drought. Economics have been analyzed for a normal year to get control multipliers. The Rand study says that we're focusing on the short term, when the issues are at the long term.

6. *Observations and Analytical Tools for Western Drought Assessment: A Status Report* (Kelly Redmond) Drought fundamentally centers on the relationships between supply and demand. Information (e.g., precipitation, soil moisture and vegetation) is needed on very small spatial scales that resolve the important topography (1/2 to 1 km). Information is also needed on a wide range of time scales, from the last few hours to the last decade or so, complete with histories to allow us to place current conditions in historical perspective. Other needs include a faster access to data from a greater number of precipitation stations, better coverage of main mountain ranges (SNOTEL), and more reference stations. Kelly noted that while satellite data are useful, they do not provide the needed depth or time resolution. The observing strategy should take advantage of small-scale clusters (NEON, CUASI) to get at high-resolution behavior, together with very clever ways of combining that information with larger-scale information.

A panel discussion followed the afternoon talks. Sitting on the panel were Don Wilhite, Doug LeComte, Chet Koblinski, and Andrea Ray, who put forward the following points:

-- Drought is a climate anomaly having a very large spatial scale. Climate signals operate on large scales, whereas climate anomalies interact at local scales (10s of meters – kilometer). How do we put these together? We're overlaying a large-scale phenomenon on something with a lot of granularity (elevations, soil types, crops, etc.). Impacts will be on small scale. We won't though be able to predict climate at those scales.
-- The Drought Monitor and Drought Outlook have been very important but are only now beginning to reach their potential for communicating to the public. Regional climatologists could provide additional background information. Other vehicles of communication include meetings of water management groups (in survey mode). Bureau of Reclamation meetings, river basin commission meetings, and so on can be effective – such meetings provide useful contacts.
-- A useful exercise would be to gather opinions and concrete ideas on the "dream" drought monitor – what would it look like, what would it do, etc.
-- The Drought Monitor has weaknesses, but it is still impressive: it's available, it reflects substantial information, it's being used for policy, and it has elevated the awareness of drought. Also, it has brought together and coordinated a variety of groups. The vegetation drought response index, combining climate information and remote sensing information, is an improved drought indicator. The product is about to become operational. A big frustration, though, is that once the research phase is over, garnering funding for operations is difficult.

Following the panelists comments, the floor was opened to all participants for general discussion. The following comments, opinions, and suggestions were made:

-- National centers can't be expected to provide very high resolution climate and drought information. Regional centers should work from the national centers' products. This is happening to an extent in New Mexico and Montana.
-- Remote sensing can bolster the monitoring program. For example, the livestock industry is big, but rangeland and pastureland are not well monitored via in situ measurements.
-- Drought has different definitions, and different users need different information. Should we "disaggregate" the Drought Monitor into different maps, specialized according to user? To some extent,

this is happening; the Drought Monitor can be considered a portal into a variety of information types. The problem, though, is that financial resources for such "disaggregation" work are very limited.
-- NOAA understands and emphasizes the need to transfer research results to operations, as evidenced by the pilot NCTP program. If a tool is fine-meshed and regionally-based but scalable, it should be taken to the national level. Resources should be redirected if necessary.
-- The Eta model already operates at fine scale, but many drought-related results haven't been carefully examined yet. A better organized, comprehensive drought website would help.
-- How do we get a more reproducible outlook? The current outlook comes out of a small-scale operation, involving 1.5 people. Do we need more resources, or more science? No new science is needed to make the drought outlook more objective; we just need more people and more organizational backing.
-- The CPC's mandate is to monitor and then forecast. This can be done at short timescales, but the trick is to translate the forecasts to the user community, with user appropriate format – that's where the work needs to be done. A conflicting opinion arose: work is still needed in the forecasting effort itself. The tool of choice for forecasts will be coupled model ensembles with sophisticated hindcasts, and this is not such a "simple" task.
-- A more physical basis is needed for the Drought Monitor. We need to learn more from attribution studies.
-- Is the western drought over? Attributions studies are relevant here. One good year in a long term, multiyear drought is often enough to "reset" planning. How things happen, in what order, is important. We may be forced into an ensemble approach to encapsulate potential sequencing. Water managers may not be ready to handle sequencing issues; they need to be educated about them.
-- We can't expect to get much from a 1+ year forecast. We have a nonstationary climate, a moving target that can't be handled by retrospective analysis. We need to know where the climate is right now, and we won't get that empirically – we need models. The CFS is a major step forward in addressing this.
-- Drought reconstructions have affected water managers in positive ways. The reconstructions of the historical and prehistoric droughts have captured the interests of water managers, opening their minds to important climate issues.
-- Predictions beyond a year or two are probably impossible, but decadal averages of El Nino behavior are probably predictable, since the controls are deterministic. This has not yet been explored. (The UKMet office, however, is producing experimental decadal forecasts.)
-- Because climate is a nonstationary system, we have a difficult time coming up with risk statistics. A contradicting opinion emerged, namely that the nonstationary trend is probably not larger than the amplitude of climate variability. In any case, the human "boundary conditions" – society's need for water and its vulnerability to drought – are nonstationary.

Wednesday AM

The second day of the workshop began with three invited overview talks, which were followed by a general discussion session.

1. *Overview and summary of the Tucson drought meeting* (Jonathan Overpeck)
Stakeholders want to know about the future possible impacts of global change. According to the USGS report "Water 2025: Preventing Crisis and Conflict in the West", the potential for water conflict is growing even in the absence of climate change.

Jonathan reviewed past droughts, with a focus on the west. The medieval period (prior to 1300) was very dry, and conditions became wetter after the little ice age. The wettest period in the last 1000 years occurred during the early 20th century – a time during which the Colorado River flow was allocated. There was also a shift in drought *variability* at about 1300AD, with more and longer droughts occurring before that time. Dunes over Kansas and much of southern plains were active 5000-10000 years ago and also 4200 years ago (200 year drought), with all of central US under drought conditions.

Questions about past climate involve issues of abrupt climate change – are they forced or unforced? Are we in a new climate regime? Do the changes represent preferred modes of climate change? The current drought is an unusually "hot drought" – superimposed on temperature-driven reductions in snow pack and forest health. A major question: is the current drought a result of global warming, or at least a sign of things to come? Previous dry periods seem to be associated, more times than not, with warm periods (and diverse forcing) in recent Earth history (i.e., during the last 10 kyrs). Paleoclimatic data also indicate that abrupt shifts to "dry climates" do happen, and that the last few centuries have been blessed with mostly "wet climates" west of the Mississippi.

2. *Understanding Origins and Predictability of Regional U.S. Drought* (Marty Hoerling)
A large ensemble of AMIP-style simulations carried out with several different AGCMs was used to study multi-decadal interior west drought, multi-annual Great Plains drought, seasonal midwest Drought, and the recent western U.S. drought. The 1956 drought was reproduced by most models, whereas the 1988 drought in the upper Midwest was not simulated by any model. (The 1988 drought was reproduced by the NCEP CFS system when land was initialized correctly, though these results must be treated with caution, since precipitation in the CFS system is rather insensitive to the land. Coupling may be important.)

For the 1998-2003 drought, different models produced very different PDFs. Issues to consider in the analysis of drought center around drought attribution (Are causes similar? How do warm-season and cold-season droughts differ? What are the relative influences of ocean and land processes?), the probabilistic nature of drought (Do more severe and/or sustained droughts occur by chance? What about the droughts that "didn't happen"?), and drought prediction (Are "skill sources" being monitored? How do we best utilize multi-model ensemble methods?) Multi-institutional efforts can play a role in such analysis.

3. *Drought: The Role of Land Processes* (R. Koster)
Land-atmosphere feedback is the process by which soil moisture anomalies produced by rainfall anomalies lead to evaporation anomalies and hence to further rainfall anomalies. Simulations with the NASA/NSIPP AGCM show that land-atmosphere feedback affects simulated JJA precipitation distributions in specific continental regions, namely, in the transition zones between dry and humid areas. Complementary analyses of historical observations strongly suggest that land-atmosphere feedback also affects the statistics of precipitation (variance) and temperature (variance and skew) in the real world, in these same regions. The expected effect on precipitation skew is not seen in the observations, perhaps because these mechanisms are muted in nature, or perhaps due to the limited data record. The impacts of feedback on precipitation and temperature have relevance for drought maintenance and prediction. Validation data are limited, but the monitoring of soil moisture does provide some forecast skill in the transition zones.

The floor was opened to all participants during the general discussion session. Several points were made:
-- The memory of near-surface soil moisture is about 1-2 months. That for the deep soil may exceed one year, though we do not have the observations to verify this.
-- The abrupt change in the year 1300 was not always a change to dry conditions; some areas turned wet. The solar output prior to 1300 was higher. We need to look further at potential issues with the interpretation of paleodata. Are the abrupt changes real?
-- We also need a better definition of "megadrought". The current definition is based on proxies that have built-in memory. Perhaps we can use tree rings with an annual resolution.
-- A global signature (paleo-evidence) of a climate shift around 1300 exists. There is also a signature of decadal La Nina variability in paleodata. We need to determine if models are capable of reproducing it.
-- What is the response to global warming – La Nina or El Nino? How good is the paleo-evidence for changes in ENSO variability? We need to consider ENSO variance versus changes in mean state.
-- Do we know the cause of the East Coast drought? Do models reproduce this drought?
-- We need models that reproduce the important modes of natural variability (and long term behavior). Simple coupled models reproduce such behavior with some success. Important questions include: why do large ENSOs occur roughly every 15-18 years followed by weak ENSOs and a tendency for La Nina conditions? What is the decadal recharge mechanism in the tropical Pacific?
-- The western dipole of winter drought is very strong this year. It is usually tied to ENSO, but ENSO conditions this year were weak. The IRI produced a very weak dipole.
-- We need to consider drought migration. Do any studies already exist? For the recent drought, we need to consider the roles of soil moisture anomalies and the low level jet.
-- An important issue is the intraseasonal variability of drought (e.g., the summer minimum in the Southwest and Mexico). The number of storms (2-3, 3-4, or 5-6) occurring during winter in the Southwest makes a large difference.
-- Models are inconsistent regarding the impact of global warming on precipitation.

Wednesday PM

The afternoon session consisted of contributed talks on drought research, followed by a panel discussion.

1. *Spatial patterns of Drought in North America from a Gridded Network of Tree-Ring and Instrumental PDSI Data, 1557-1990*. (Connie Woodhouse and Edward Cook)
This talked addressed several questions, including: What are the major drought patterns across the study area? How are the pattern types distributed over time? Over periods of persistent drought, do spatial modes also persist? A rotated PCA shows two main patterns: an ENSO-like pattern and an east/west drought contrast. Two other patterns show region-wide droughts centered on parts of the Great Plains. Some years of widespread drought can be matched with one dominant pattern, but more often the loadings are spread between 2 or 3 co-dominant patterns. If patterns can be linked to causal mechanisms, then in many years, widespread drought results from a mix of mechanisms.

2. *Tree-ring records of prolonged drought from Canada's western interior* (David Sauchyn)
The critical characteristic of drought affecting ecosystems and human populations is duration. Ten- to twenty-year periods of predominately below average annual precipitation occurred in the 18th and 19th centuries shortly before settlement of the northern plains. A significant research topic is the cause of prolonged drought and multi-decadal shifts in aridity, which are evident only in paleoclimatic records.

3. *Extending the current CPC US soil moisture related forecasts to a North American domain* (Huug van den Dool and Yun Fan)
The current configuration for the CPC soil moisture-related forecasts is for the United States (land only), with 102 Climate Divisions. The model used is the so-called "Leaky Bucket", the data period is 1932-present, and the temporal resolution is monthly (hybrid daily for real time applications). This configuration is being extended to cover North America (12.5-72.5N, 170W-50W) as a gridded domain at 0.5X0.5 resolution. The "Leaky Bucket" is still being used, but with ice/snow updates. The data period for the new configuration is 1948-present, and the temporal resolution is again monthly.

Several issues still need consideration: (1) How about extending to the ocean as well? (How do we merge land and ocean? How do we treat anomalous evaporation?) (2) Should we extend the configuration to other continental domains? (Why not whole world at once?) (3) How trustworthy are the soil moisture data? (4) How do we verify the results? Process studies are need to address these and other issues.

4. *A drought monitoring and early warning system for the United States* (Kingtse Mo and Wayne Higgins)
The experimental Drought Early Warning System (DEWS) is intended to be an integral component of national policy to monitor and predict drought in support of the NIDIS. The system will allow us to: (1) improve the monitoring of drought based on historical observations and near-real-time regional analyses, including output from NLDAS; (2) examine physical mechanisms related to drought for better monitoring and prediction; and (3) assess the capability of the NCEP CFS to forecast drought conditions. The performance of the new CFS model, including the LDAS as a subcomponent, will be diagnosed. Intentions are to develop and implement the experimental DEWS based on the dynamical forecasts and the regional analysis/NLDAS.

5. *Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000* (Richard Seager, Yochanan Kushnir, Celine Herweijer and Naomi Naik)
An analysis focused on two sets of numerical experiments, one in which an Atmosphere GCM was forced by historical tropical Pacific SSTs since 1856 and was coupled to mixed layer ocean elsewhere (POGA-ML), and the other in which an Atmosphere GCM was forced by global SSTs since 1856 (GOGA). The analysis highlighted six extended North American droughts in the instrumental record: 1856-1865, 1870s, 1890s, 1930s, 1950s, and Turn-of-Century. Every one of the droughts was forced by weak but persistent La Ninas, as demonstrated by the POGA runs. Feedback, or forcing, from other oceans was not clear in these GCM experiments and may not be important. The North American droughts fit into a global pattern of hydroclimatic variability with distinct hemispheric and zonal symmetry. The mechanisms involve

tropical SST-subtropical jet-transient eddy-MMC interactions (for symmetric response) and Rossby wave teleconnections (asymmetries). The prediction of extended drought requires prediction of tropical Pacific SSTs on multiyear timescales. (Is this possible?) Further results on the historical drought were presented in a poster by Celine Herweijer entitled "North American Droughts of the mid-late 19th Century: a history, simulation & implication for Medieval drought".

6. *Tropical influences on interdecadal variability in precipitation over the Americas: The case with 1976/77 transition* (Huei-Ping Huang, Richard Seager, and Yochanan Kushnir)
The post-1976 epoch (July 1976-Jun 1998) and pre-1976 epoch (July 1961-Jun 1976) periods are compared in atmospheric model simulations forced with observed SSTs (both global and tropical Pacific SST runs– see description above of Seager's talk). The results provide evidence that interdecadal precipitation anomalies over the Americas are forced by tropical SSTs; the POGA-ML simulation produced results as good as the GOGA run did, indicating the influence of tropical Pacific SST. The Pan-American precipitation pattern consisting of wet over Mexico/southwest US, dry over the northern South America, wet over central S. America, and dry over the southern tip of S. America appears to be a response to warm tropical Pacific SST. The increase in precipitation over land is balanced mainly by moisture convergence due to changes in low-level wind divergence (related to ascent/descent). An exception is the southwestern U.S., where evaporation is important.

7. *25 Years of global water vapor back-trajectory analysis - Droughts, floods and recycling regimes*. (Paul Dirmeyer and Kaye Brubaker)
NCEP/DOE reanalyses are used to track multiple "parcels" back in time from observed precipitation events, estimating evaporative contributions along the way based on ET rates and TPW. The parcels are launched at random humidity-weighted altitudes. Evaporative sources were compared for various regions and for the three driest and three wettest years. It was found that humid mid-latitude basins are usually not starved for ET even during droughts, so recycling is highest then. Floods tap oceanic moisture sources, reducing recycling. Semi-arid basins like the Murray show the lowest recycling during droughts. Further needed work includes a more thorough examination of the basin-scale properties of evaporative sources, recycling, and changes during drought and flood periods, and the characterization of regions based on the drought/flood recycling regimes.

8. *The role of North American orography on Great Plains low-level jet* (Mingfang Ting)
Two key questions were addressed in this talk: what causes the Great Plains LLJ to change its strength on the interannual time scale, and what causes the Great Plains LLJ to exist in the first place? The results of AGCM simulations with and without North American topography showed that: 1) the presence of the Great Plains LLJ depends strongly on North American topography, 2) the dominant mechanism by which the topography supports the LLJ is through mechanical blocking of the trade winds from the Atlantic and the resultant northward deflection of the flow, and 3) both thermal forcing and the transient modification due to topography is much smaller than the mechanical blocking effect. The results suggest that prediction of LLJ variability, and thus the U.S. summer precipitation, may depend strongly on the accurate prediction of the North Atlantic subtropical high and the related trade wind strength and location.

9. The structure and nature of warm-season interannual variability of the Great Plains hydroclimate *(Alfredo Ruiz-Barradas, and Sumant Nigam)*
An analysis of observations and the NCEP North American Regional Reanalysis show that remote water sources dominate over local water sources (precipitation recycling) in the generation of precipitation variability. Also, the Pacific's link with the Great Plains hydroclimate is through northeastward moisture transports across the Gulf of California, at mid-troposphere levels. The Atlantic connection, on the other hand, is through the NAO's influence on the Bermuda High and the resulting interaction of circulation with North American orography, all of which serve to modulate the low-level moisture transports from the Gulf of Mexico.

10. *Numerical simulation of Mississippi River Basin water cycle: Relationships between soil moisture, SST and precipitation recycling* (Mike Bosilovich)
In a numerical experiment, AGCM in-line water vapor tracers kept track of water evaporating from specified source regions. The model was run at 2°x2.5° degree resolution for the period 1948-1997 and

included a total of 40 tracers. The results encompass all GEWEX CSE's, but the focus in this talk is on MRB (Mississippi River Basin), along with some results for MAGS and LBA. The percentage of evaporated water that stays in a region is as follows: MAGS=17.7%; MRB=22.5%; LBA=52.2%. A region's recycling rate depends on prevailing moisture transport and evaporation. It is important to consider all sources of water (local and remote) in assessing land-atmosphere interaction impacts on climate anomalies.

11. *On the role of the Intra-Americas Sea in water vapor transport to North America* (Alberto Mestas Nunez)
The overall goal of this research is to investigate the role of the warm pool of the Intra-Americas Sea (IAS) in supplying the moisture that feeds warm season precipitation over North America. The NCEP/NCAR global reanalysis cannot close the IAS moisture budget due to large uncertainties in P. However, the IAS moisture divergence from the NCEP/NCAR reanalysis compares well with E-P from ERA15 and Southampton unconstrained estimates. Generally, moisture fluxes are divergent (E exceeds P) over the IAS, indicating that the IAS is a moisture source. The global reanalysis can be used to study the variability of the IAS water vapor fluxes. The variability of the northward moisture flow from the IAS is related to precipitation over North America throughout the year. The contrast in SST between the Gulf of Mexico and the Caribbean Sea when the Gulf is warmer than usual is the dominant driver of the northward moisture flow. This IAS SST pattern is part of the larger-scale Pacific North American (PNA) pattern. Also, the main moisture source is the Gulf of Mexico and the region just east of the IAS in the North Atlantic.

12. *Long-term soil moisture variability from a novel diagnostic approach and drought impact on the ecosystem* (Ning Zeng)
Several methods were examined to estimate soil moisture. The P-E-R method provides a unique opportunity to diagnose basin-scale long-term soil moisture variability for the 20th century, generally not available from any other method. The P-E-R method thereby provides a potentially valuable tool for validating land-surface models. Interannual variability over the Amazon is about 200-300mm, consistent with recent (albeit limited) satellite gravity inference. Land-surface models tend to underestimate significantly such variability. Decadal and longer variability can be up to 500-600mm, but uncertainty is also large on longer time scales. The moisture convergence method, unfortunately, has large errors in capturing the precipitation/MC variability as a result of problems with the reanalyses due to changes in the observational system, bias in the tropics, etc.

13. *Predicting drought in South America: Seasonal and sub-seasonal (in a nested-modeling framework)* (Anji Seth)
Where predictability on seasonal timescales exists, there is substantial interest in higher frequency information (onset/demise of rainfall, dry spells, etc.). The abilities of several different models and boundary conditions to produce such information in South America were compared. Preliminary conclusions were that for the annual cycle, the RegCM/Emanuel model improves the simulation of rainfall, sea level pressure, and moisture transport compared with Grell and is comparable with the GCM. The interannual variability in the Northeast is well captured by all the models. The relationship of the variability in the southeast to ENSO is weak in the RegCM/Grell model and appears to be improved in RegCM/Emanuel. The RegCM shows potential to add value (compared to the GCM) to estimates of the onset, demise and length of the rainy season. For dry spells, the work is just beginning. The Emanuel scheme appears to improve many (though not all) aspects of the simulation.

14. *Land surface-atmosphere interactions over North America based on NARR products* (Hugo Berbery)
Two key questions were addressed in this presentation: what are the local mechanisms that enhance or weaken atmospheric anomalies, and where are land-atmosphere interactions strongest (or weakest)? The research focused on North American basins with diverse climate regimes: (1) the Mississippi basin, with summer precipitation associated with the LLJ; (2) the western United States basins, with complex topography and significant cold season snowfall, and (3) the monsoon prevalent regions, with a strong summer hydrologic cycle associated with the North American Monsoon. The results show regional variations in the strength of the link between soil moisture and precipitation.

A panel discussion was held after the afternoon talks. The points and unresolved issues below were expressed either by the panelists (Jonathan Overpeck, Marty Hoerling, and Randy Koster) or by the audience at large:
-- The dynamical understanding of drought on different time scales is important. Is there a role for SSTs other than through ENSO? What are the teleconnections that lead to remote responses and consequent drought?
-- On decadal time scales, droughts over North America can be related to tropical SST forcing. It is not clear which aspects of the SST forcing are important. What must we do to gain the necessary understanding? What is the decadal predictability of tropical SSTs?
-- We need a coordinated and comprehensive effort addressing the attribution of droughts at different time-scales (e.g., through analysis of C20C runs). What are the relative roles of natural variability and boundary conditions? What is the influence of local feedback and the land-atmosphere connection? A successful drought prediction activity requires a successful attribution study.
-- If the skill of precipitation prediction is low, is a useful drought prediction activity possible? Or is precipitation is just one facet of a drought prediction activity? If yes, in what sense? Is a more skillful surface temperature prediction also useful for drought prediction? Could one also predict derived products, e.g., vegetation index?
-- We need a working definition for drought and for its initiation and termination. Sectoral definitions may be necessary.
-- What are the observational needs for drought monitoring? Do we need improved SST measurements? Direct measurements of soil moisture, as well as derived estimates (e.g., via LDAS), will be important.
-- A drought early warning system will require assessments of soil moisture at different depths, and/or will require a soil moisture monitoring system at different depths.
-- We need to conduct a coordinated set of numerical experiments to establish classical predictability limits for soil moisture and its impact on atmospheric circulation. Are these predictability limits different for the initiation and termination phases of drought? Can the initiation of droughts be predicted when starting from normal soil moisture conditions? Are the existing small predictability estimates of ~1-2 months a result of model deficiencies?
-- We need a coordinated set of numerical experiments – some with and some without land-atmosphere interaction – to understand the atmosphere's control of soil moisture anomalies and vice-versa. What is the vertical extent of the influence of soil moisture anomalies on the atmosphere?
-- Establishing predictability/predictions of both hydrological and agricultural droughts is important.
-- Probabilistic conditional drought information (conditional to ENSO etc.) must be considered. Staging the drought information and forecasts ??? .
-- For predictions on decadal timescales, we don't have to predict exactly the sequence of SSTs. We might only need to predict the slight "tilt" (trend) in the SSTs.
-- Stakeholders are more interested in the recurrence of decadal droughts, and they will find a source for this information when needed – even if the source is unreliable.
-- Do mega-droughts and seasonal droughts have the same underlying physical mechanisms? What role does the slow memory of deep soil play in the maintenance of long-lasting droughts?
-- What is the role of climate change in drought?

V. Workshop Agenda

Tuesday May 17

0830 **Opening remarks:** (S. Schubert)

0840 Chet Koblinsky –NIDIS planning at NOAA
0850 Jared Entin – NIDIS planning at NASA

Invited overview talks

0900-0930 *Don Wilhite* – Moving from Crisis Response to Drought Risk Management: Shifting the Paradigm
0930-1000 *Doug LeComte* – Drought Monitoring and Prediction: Challenges and Opportunities
1000-1015 break
1015-1045 *Chet Ropelewski/Walter Baethgen* –Latin American issues and applications
1045-1115 *Andrea Ray/Roger Pulwarty* – Water resources and drought: critical information needs

1115-1145 **Discussion**

1145-1300 **Lunch**

1300-1430 **Poster viewing** (posters will be up for viewing during the entire workshop)

Barrie Bonsal and Elaine Wheaton- "Atmospheric Circulation Comparisons Between the 2001 & 2002 and 1961 & 1988 Canadian Prairie Droughts"
Ken Snelgrove, S. Yirdaw-Zeleke, E.D. Soulis, F.R. Seglenieks - GRACE (Gravity Recovery and Climate Experiment) Measurements for Drought Monitoring?
Maria Tereza Cavazos Perez and Sasha Gershunov - "Variability and predictability of North American monsoon droughts"
Celine Herweijer, Richard Seager and Edward R. Cook, "North American Droughts of the mid-late 19th Century: a history, simulation & implications for Medieval drought"
Phil Englehart and Art Douglas – Connecting intraseasonal rainfall variability and the SPI: Some regional examples from Mexico
Kostas Andreadis, Elizabeth Clark, Andrew W. Wood, Alan F. Hamlet, and Dennis P. Lettenmaier – 20th century drought in the coterminous U.S.
Phil Pegion, Siegfried Schubert, Max Suarez, and Randy Koster - On the Nature of the Recent SW US drought
David Legler and C. Stephens – U.S. CLIVAR – The US contribution to the Program on Climate Variability and Predictability
Robert S. Webb, Connie Woodhouse and Gregg Garfin – Developing Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin
Justin Sheffield and Eric Wood – "The development of a simulated soil moisture analysis for the US for real time monitoring and seasonal forecasting of drought"
Tsegaye Tadesse, Jesslyn Brown, Michael Hayes, Don Wilhite, and Mark Svoboda - A data mining approach to monitor vegetation stress due to drought: integrating satellite, climate, and biophysical data over the U.S. central plains."
Andy W. Wood, Ali Akanda, and Dennis P. Lettenmaier – An Experimental Daily US Surface Water Monitor at the University of Washington
Wayne Higgins – NAME contributions to drought monitoring and prediction
Ian Ferguson, Philip Duffy, S. Schubert, Philip Pegion and Xu Liang – Potential Predictability of Drought in the Western U.S.
Shaleen Jain, Martin Hoerling, and Jon Eischeid – Decreasing reliability and increasing synchroneity of western North American streamflow

1430-1630 Applications - 15 minute talks

1430 *Paul Houser* - Enhancing water management applications with surface observation and modeling
1445 *Ted O'Brien and Aston Chipanshi*– The search for improved drought monitoring tools, issues and applications in Canada.
1515 *Tim Brown* **-** Drought and Wildland Fire Management
1530 *Jozef Syktus* - The Application of Climate Information and Models in Monitoring Drought and Risk of Land Degradation in Queensland
1545 *Upmanu Lall* –canceled
1600 *Roger Pulwarty and Mike Hayes* - Estimating the economic impacts of drought
1615 *Kelly Redmond* - Observations and Analytical Tools for Western Drought Assessment: A Status Report

1630-1645 break

1645-1800 Panel discussion on status of drought monitoring and information needs.

Panel – Invited speakers - Don Wilhite (chair)

1) Current capabilities/products (drought monitoring and information)

what is available and how useful is it?

2) What are the critical needs?
-predictions - quantities, time scales, usefulness in the face of uncertainty
-observations – data sets (e.g., historical droughts, monitoring needs)
-understanding the causes of drought
-conveying information (optimal use of PDFs)
-quantifying the economic benefits of drought predictions

Wednesday May 18

Invited overview talks

0900-0930 *Jonathan Overpeck* – Overview and summary of the Tucson drought meeting
0930-1000 *Marty Hoerling* – Understanding 20th Century Regional Droughts
1000-1030 *Randy Koster* – Drought: the role of land processes

1030-1045 Break

1045-1145 Discussion – poster viewing

1145-1300 Lunch

1300 Research - 15 minute talks

1300 *Connie Woodhouse and Edward Cook*– Spatial patterns of Drought in North America from a Gridded Network of Tree-Ring and Instrumental PDSI Data, 1557-1990
1315 *Dave Sauchyn* - "Tree-ring records of prolonged drought from Canada's western interior"
1330 *Huug van den Dool and Yun Fan* – Extending the current CPC US soil moisture related forecasts to a North American domain

1345 ***Kingtse Mo and Wayne Higgins*** **– A drought monitoring and early warning system for the United States**
1400 *Richard Seager, Yochanan Kushnir, Celine Herweijer and Naomi Naik* – Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000
1415 *Huei-Ping Huang, Richard Seager, and Yochanan Kushnir* – The 1976/77 transition in precipitation over the Americas and the influence of tropical SST
1430 *Paul Dirmeyer and Kaye Brubaker* - 25 Years of Global Water Vapor Back-Trajectory Analysis - Droughts, Floods and Recycling Regimes.
1445 *Mingfang Ting* - The Role of North American Orography on Great Plains Low-Level Jet

1500-1530 **Break**

1530 *Alfredo Ruiz-Barradas, and Sumant Nigam*- The structure and nature of warm-season interannual variability of the Great Plains hydroclimate
1545 *Mike Bosilovich* – Numerical simulation of Mississippi River Basin water cycle: Relationships between soil moisture, SST and precipitation recycling
1600 *Alberto Mestas Nunez* - On the role of the Intra-Americas Sea in water vapor transport to North America
1615 *Ning Zeng* – Long-term soil moisture variability from a novel diagnostic approach and drought impact on the ecosystem
1630 *Anji Seth* – Prediction of Drought in South America including Seasonal Drought and Subseasonal Dry Spells
1645 *Hugo Berbery* – Land surface-atmosphere interactions over North America based on NARR products

1700-1800 **Panel discussion on Research Priorities and charge to participants for Thursday session**

Panel – Invited speakers – Jonathan Overpeck (chair)

1) Current understanding and drought prediction capabilities
time scales, regions, quantities, uncertainties, methodologies

2) Research/modeling/observation priorities:
- modeling issues
- prediction capabilities
- observations
--research priorities

Thursday May 19 (AM)

Panel Discussion – (panel consists of organizing committee)

0900-10:30 Summary and Discussion

intersection of needs and current and future capabilities
how do we strengthen research/applications links and feedbacks?
Interagency coordination, NIDIS priorities, funding outlook

1030-11:00 "Working" break – presentation of "straw-man" recommendations

1100-12:00 Finalize Recommendations

Priorities for research, observations
A framework for experimental drought prediction and attribution

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Appendix: A National Drought Attribution and Prediction Consortium

The following outlines the goals and activities of a multi-agency **National Drought Attribution and Prediction (NDAP) Consortium**. NDAP is recommended as a high priority initial coordinating and focusing activity of the prediction program.

The purpose of the NDAP consortium is to: *coordinate, develop and assess the utility of model-based predictions and hindcasts of drought and related climate factors on subseasonal to decadal time scales*.

It is anticipated that NDAP would carry out near real time prediction/attribution activities as well as other relevant (non-real time) drought research as outlined below. The consortium would have base-level multi-agency funding to support a core activity and facilities. Community participation would be through announcements of opportunity aligned with agency goals and programs.

<u>Participants</u>

drought monitoring, prediction and analysis communities; relevant modeling and data assimilation centers; applications communities (e.g., agriculture, water management, policy makers, etc.)

<u>Funding</u>

Interagency funding to help implement NIDIS/IEOS strategic plan
(base-level funding for core activity plus AOs for community participation)

<u>Examples of NDAP activities</u>

- multi-model attribution of changes in recent weather activity (e.g., nature of increased storminess, extreme events, do they signal the end of drought?)
- evaluate the utility of (and provide direction for future) in situ and space-based observations for improving predictions based on, e.g., observing system sensitivity and/or simulation experiments
- assess multi-(hydrological) model predictions of soil moisture and run-off
    - attribution: memory of land versus other forcing (e.g., SST)
    - short versus long term variability
    - develop improved estimates of PDFs
- assess multi-model (coupled) predictions of global links of drought to seasonal SST changes (e.g., ENSO)
- assessment of long term SST changes, and impact on multi-year drought (e.g., can we identify and ultimately predict the key factors important for the development and demise of multi-year drought)
- assess utility of model-based predictions of vegetation changes, crop models
- assess the sources of uncertainty in the predictions including both model errors and uncertainties in the initial conditions
- coordinate model simulations, forecasts
- work with applications communities to tailor products and educate users
    - ensure prediction and attribution products are useful to user communities (space and time scales, quantities, etc.)
- monthly conference calls coordinated with existing drought monitoring activities
    - help improve physical basis of drought monitoring
    - development of a drought early warning capability

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