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CLIMATE CHANGE AND WATER: A LONG-TERM PERSPECTIVE

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Thank you Harold, and thank you Bob, and thank you to all of you who are joining us at this Symposium. I absolutely love being at the Buffalo Bill Historical Center and I greatly admire the work that you do that is not only keeping exhibits in a wonderful and beautiful and dynamic state, but also populating the museum with interested citizens.

The reason we are here is, in part, because of the drought that overtook the U.S. from 1999 to 2004 and brought issues of water into focus. The good news is that the drought by and large has subsided. We can now reflect a bit on what was special about that drought of the last several years. If you

* Dr. Lisa J. Graumlich's position as Executive Director of the Big Sky Institute for Science and Natural History at Montana State University allows her to combine her career-long interest in mountain regions and natural areas with her concerns for sustainability. As a researcher, she uses tree-ring records to investigate how climate variation affects forest dynamics and disturbance processes such as wildfire. Dr. Graumlich is also active in developing programs and institutions that bring interdisciplinary science to bear on sustainability of ecosystems and communities.

In 1993, she was chosen as the first Director of the University of Arizona's Institute for the Study of Planet Earth (ISPE). While Director of ISPE, she developed an integrated program of research, education, and outreach focusing on the impacts of climatic variability on semi-arid regions. In 1999, she moved to Montana State University to direct the Mountain Research Center (MRC). In 2001, she was selected as the Executive Director of MSU's Big Sky Institute (BSI). Her goal for BSI is to develop an integrated program linking science, education, and decision making in the Greater Yellowstone Ecosystem and other similarly large and complex ecosystems.

Dr. Graumlich received her Ph.D. from the University of Washington (1985). She was named an Aldo Leopold Leadership Fellow in 1999 and was elected as Fellow of the American Association for the Advancement of Science in 2004.

look at this map of the Palmer Z indices for March of 2004,[1] you see a common way climatologists portray the severity of drought. You see from the colors in the West that this drought was severe in part because it went from the Mexican border up to the Canadian border, it affected the southwestern United States, and it lasted for what seemed like an eternity. So it was big, it was severe, and it lasted a long time. That clearly had implications for water. Here is a photo of the Lake Powell data from toward the end of the drought from 2002-03.[2] You can see the dramatic lowering of water levels in Lake Powell. This type of dramatic response to a drought challenges us to ask deeper questions about the availability of water in the future.

Well, as we look to the future, we have some tools that are more or less helpful to this discussion. I am going to start with tools that probably don't help us move forward in thinking about water management in the West. In this I show a set of comparisons between observed and predicted precipitation from one of the most sophisticated global climate simulation models we currently have.[3] The projections, especially with respect to winter precipitation in the West are difficult to interpret. So when we use these models to look to the future of water, we don't have a science-based prediction that is really useful to those of you who are involved in policy debates.

The climate models are starting to provide consensus about the future of temperatures in the West. All of the models agree that over the next couple of hundred years the earth will warm up. On some levels that is old news to anybody who has been tracking the timing of spring snowmelt. In this graph, the size and color of circles indicate the degree to which spring snowmelt is tending to be earlier (red circles) or later (blue circles) as compared to the long-term record.[4] We can see that in the vast majority of the Pacific Northwest the timing of spring snowmelt, as indicated by the hydrographs of the rivers in these regions, is anywhere from five to twenty days earlier than usual. These data are indications that we are starting to experience the impacts of rising temperatures on water systems.

Today I want to share with you some of the results from my research group and our colleagues who have taken a different tack on how we might anticipate the future, namely by trying to better define what is "normal" for

1. Photograph of the Palmer Z Indices, Mar. 2004, http://bsi.montana.edu /staff/graumlich/wylawreview. *See also* The National Drought Mitigation Center, http://drought.unl.edu/index.htm (providing additional information on drought indices and monitoring) (last visited March 26, 2006).

2. Photographs of Lake Powell (2002-2003) http://bsi.montana.edu (depicting changes in lake levels).

3. William D. Collins et al., *Community Climate System Model: CCSM3*, http://www. ccsm.ucar.edu/publications/jclim04/Papers/SSC1.pdf (discussing results of climate simulation models).

4. Iris T. Stewart et al., *Changes Toward Earlier Streamflow Timing in Western North America*, 18 JOURNAL OF CLIMATE 1136-1155 (2005).

the climate system. When we ask that question, namely "what is normal," and look to weather records in the West, it is a frustrating endeavor. If we are lucky, the weather stations go back a hundred years. In most cases in the mountains of the West where the water supplies are generated from snow pack, those records are much, much shorter. We are lucky if we have records that go back to 1950 and that doesn't allow us to characterize long-term trends. For this reason, I have made a career of using tree-ring records to look back in time and have found some surprising discoveries.

My career started at UCLA where I was an assistant professor in the 1980s. I went to the Sierra Nevada looking for records of past climate. In the Sierra Nevada there are many sites on the eastern slope that are very dry due to the rain shadow. I concentrated on extracting samples from foxtail pines, a species that commonly lives to 1000 years or more and are closely related to the more famous bristlecone pines. We collected hundreds of samples from trees from Yosemite to the Sequoia National Parks and brought them back to the lab to measure the rings. We found something that was disturbing to me. There were periods of sustained slow growth for two different periods, one in A.D. 1000 and the other in A.D. 1300. If we did the math right this implied that there was a drought period more severe than the Dust Bowl that lasted about four times as long.

This kind of drought was inconceivable to me at the time so I rechecked the measurements and the analyses. There didn't appear to be any flaws in the analyses and so I cautiously published a scientific article that was filled with caveats about the nature of those droughts.[5] Shortly after it was published, I was excited to make contact with Scott Stine, who was finishing his Ph.D. at the University of California Berkeley. Scott took advantage of the fact that the water levels of Mono Lake had been reduced by exports of surface water to southern California. In the course of extensive fieldwork along the shores of Mono Lake Stine found tree stumps rooted in place that had previously been under water.[6] They were very well preserved and had a hundred rings or more on them that could be radiocarbon dated.

Stine discovered that Mono Lake tree stumps fell into two groups according to date of establishment: one group around 1000 A.D. and one around 1300 A.D. These dates indicate that, without the influence of humans, Mono Lake dropped by 15 meters for two periods back in time that perfectly coincided with my droughts. There is other evidence from tree stumps that can be seen rooted in place in the Walker River that indicate extended, reduced river flow during these periods. To further validate these

5. Lisa J. Graumlich, *A 1000-year Record of Temperature and Precipitation in the Sierra Nevada*, 39 QUATERNARY RESEARCH 249-255 (1993).

6. Scott Stine, *Extreme and Persistent Drought in California and Patagonia During Mediaeval Time*, 369 NATURE 546-549 (1994).

findings, we went back even farther and, using those venerable bristle-cone pines, reconstructed precipitation back 8000 years. Once again, we found droughts around 1000 and 1300 A.D., and in addition we could see that droughts more severe and persistent than what we've seen in the twentieth century have occurred about once per century for the last 8000 years.[7]

The information I have presented thus far centers in California but it turns out that the same droughts extended over large parts of the western U.S. When we look at tree-ring reconstructions of precipitation extending back 600 years or more at sites in Mexico up into Canada,[8] we see a late 16th century drought spanning the West that lasted about forty years. These results and many others like them strongly support the idea that when we get a severe drought, it tends to extend over the entire West.

What causes these droughts to persist? We know that it has something to do with Pacific sea surface temperatures. That is not a foreign concept to anybody that has paid attention to weather over the last several years. We certainly know that El Niño and its companion pattern, La Niña, spawn weather anomalies in which the jet stream steers storms into the Southwest or into the Pacific Northwest. The steering tends to persist over one or more years and thus generate regional droughts. It turns out that patterns of Pacific sea surface temperatures persist, not just for a couple of years, but for decades at times. Climatologists describe one of these patterns as the Pacific Decadal Oscillation (PDO), which at times has been referred to as El Niño on steroids because of its strength and persistence.

When climatologists aggregate Pacific temperatures into an index for the PDO[9] during the twentieth century, they see that not only do these patterns persist, but they tend to change relatively rapidly. In the first part of the twentieth century we were in what is referred to as a positive phase, which tends to bring drought to the northern Rockies, and then we switched relatively rapidly in the 1940s into a cool phase, which brings abundant moisture to the northern Rockies. In the 1970s the pattern changed back into this warm phase bringing drought to the northern Rockies.

Research on the Pacific Decadal Oscillation allows us to understand the pattern of abundant rain in the Northwest, drought in the Southwest, or vice versa. But it didn't explain those droughts that spread over the entire

7. Malcolm K. Hughes & Lisa J. Graumlich, *Climatic Variations and Forcing Mechanisms of the last 2000 Years*, in NATO ADVANCED STUDIES WORKSHOP SERIES (Springer-Verlag 1996) (listing multimillennial dendroclimatic records from the western United States).

8. Thomas W. Swetnam & Julio L. Betancourt, *Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest*, 11 JOURNAL OF CLIMATE 3128–3147 (1998).

9. Nate J. Mantua et al., *A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production*, 78 BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY 1069–1079 (1997).

West. That is because we were ignoring another center of action, the Atlantic Ocean. In the same way we get particular patterns of sea surface temperatures in the Pacific, we know that warm temperatures in the Atlantic not only create more hurricanes in the Southeast, but actually affect Western weather as well. The Atlantic Monthly Oscillation (AMO) has been documented as patterns of sea surface temperature that persist for 30, 40, or up to 50 years at a time. The AMO switch in 1997 to warmer conditions in the north Atlantic appears to be correlated with Western drought.[10]

What does this mean for water resources in the West? Recently, my research group developed a tree-ring reconstruction of precipitation for Yellowstone extends back 1173.[11] There are a couple of things that we found in this record. The twentieth century was relatively wet compared to this long period. Secondly, we have a distinct oscillation from dry to wet to dry that occurs quickly rather than slowly. The precipitation reconstruction also shows us that droughts like the Dust Bowl, or ones even more severe, occur about two times per century. We are increasingly confident that these droughts are linked to sea surface temperatures driven by internal ocean dynamics. And, we know that mega-droughts that extend from northern Mexico to the Canadian border appear to occur about every 500 years. So, extreme and persistent droughts should be thought of as a normal part of the climate system.

As we look forward to the other speakers in the program, one might ask who cares. People who try to come up with sensible policies for water should care. A dilemma that we face currently, for example, is the allocation of the Colorado River water. The Colorado River Compact, which, in 1922 was set up based on what was at the time the "best" data.[12] At that point in time, people had measured the flow at Lees Ferry from 1899 to 1922. Resource managers and politicians came up with an estimate of the normal flow of the River as being 16.4 million acre feet and used that figure to allocate water between the Upper and Lower Basin. This arrangement persists to this day and is the basis for a wide-ranging set of institutional arrangements.

Is 16.4 million acre feet normal? When we use tree rings to reconstruct flow back through time we see that such a value is anything but normal. It turns out that 1900-1920 was the wettest period in the last 420

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10. Greg J. McCabe et al., *Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States*, 101 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES 4136–4141 (2004).

11. Stephen T. Gray et al., *Annual Precipitation in the Yellowstone National Park Region Since A.D.* QUATERNARY RESEARCH 1173 (2006).

12. Robin H. Webb et al., *Climate Fluctuations, Drought, and Flow in the Colorado*, U.S. Geological Survey Fact Sheet 3062–04, U.S. Department of the Interior. Lakewood, Colorado (2004).

years.[13] In conclusion, when we think about water in the West, we should be thinking seriously about decade and longer fluctuations in precipitation. The potential clearly exists in the future for droughts of greater severity than the Dust Bowl. And these persistent droughts or wet periods tend to solidify institutional arrangements. The biggest caution here is to not let those institutional arrangements become so entrenched that we become less able to adapt. And, it is that adaptability, whether it is through pricing or other kinds of mechanisms that is the key allowing us to live with drought as an inevitable part of life here in the West. Thank you.

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13. Charles W. Stockton and Gordon C. Jacoby, *Long-term Surface Water Supply and Streamflow Levels in the Upper Colorado River Basin*, 18 LAKE POWELL RESERVOIR PROJECT BULLETIN 70 (1976).