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THE EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES IN THE WEST:

INTRODUCTION AND OVERVIEW

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In the summer of 2000, the United States Department of Energy (DOE) funded a project to perform an experimental "end-to-end" assessment of the effects of climate change on the western United States. The project was intended both to demonstrate and test a methodology for performing quantitative assessments of climate-driven environmental impacts and to provide useful information to regional, state, and local decision-makers whose job it will be to deal with the conflicting demands that climate change, population increases, and economic growth will place on the water resources of the West. The third objective, was to demonstrate the potential value of an Accelerated Climate Prediction Project (ACPI). The ACPI was a DOE initiative to accelerate the development, improvement, and application of U.S. climate models and to provide the advanced computational facilities that would be needed to carry out this work. The ACPI initiative was in direct response to the National Academy of Science's 1998 warning that "*The United States lags behind other countries in its ability to model long-term climate change. …it is inappropriate for the United States to rely heavily upon foreign centers to provide high-end modeling capabilities*" (National Research Council 1998). Although the ACPI was not funded, some of its spirit lives on in various DOE and other federal agency projects and programs designed to advance "ultra scale" computing and the science of climate simulation. In this volume, we hope to demonstrate what can be achieved if a highly qualified group of scientists are brought together – under relatively light management reins – to take an in-depth look at how future climate change might affect issues of real importance to the citizens of the United States.

Other assessments have been made of the potential effects of climate change on the West (National Assessment Report, 2000), but this current work differs from previous assessments in important ways. The principal differences are

1. This assessment was performed as a coordinated project; thus, the researchers who were conducting the impact assessments were able to influence performance of the climate model simulations and the data products these simulations produced. This interaction was very important in facilitating the end-to-end assessment approach.
2. The global climate model used to produce the climate scenarios, the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM), is one of the more conservative in terms of its climate sensitivity (i.e., the degree of climate warming predicted for a given increase in atmospheric greenhouse gas

concentrations); thus, the predicted impacts might be considered a "best-case" future scenario.

3. Particular emphasis was placed on changes over the next 50 years, and multiple model realizations were employed to indicate the range of climate variability.
4. Results from the global model were down-scaled using both dynamic regional climate models and statistical techniques in order to gain improved representation of the dominant influence of topography on local climate and to provide climate information at the scales needed for simulating hydrological response.
5. Water resource assessments were focused on three major Western river systems – the Columbia, the Sacramento/San Joaquin, and the Colorado. In addition, an assessment was performed of the potential effects of climate change on fire weather. These latter two assessments – water resource impacts for the Colorado River basin and fire weather – are the first quantitative assessments of these issues.

This project did not examine the effects that growth in demand, due to population increase and economic growth, might have upon these resources. These effects would be considerable, but they were simply outside the scope of the study. The emphasis here is on the effect of climate change on the system as it stands today. Growth is another stress that would be applied to a system that in many places may be approaching its current limits of adaptability.

Project Implementation

The ACPI Demonstration Project was implemented as three distinct elements. These elements are depicted in Figure 1. Element 1 used existing ocean observations and inverse techniques to quantitatively establish the observed physical state of the global ocean at the end of the 20th century. This information served as initial conditions for the coupled global climate model (Element 2) that was used to produce climate change scenarios for the next century. The third program element downscaled these large-scale predictions of the global model to ensembles of regional scale predictions for the western United States. These predictions were then used to estimate local impacts on water resource availability and on water-dependent activities or resources such as hydroelectric power generation, irrigated agriculture, and stream habitat,

Element 1: Ocean Assimilation

It has recently become possible to assimilate observed ocean data on a global scale, thereby producing gridded fields of such quantities as temperature, salinity and velocity for the world oceans. The capability to produce these fields results from improvements in ocean models, adjoint and filtering techniques, computer speed, and major observational campaigns (e.g., WOCE, TOPEX/Poseidon, etc.). The status of the assimilation effort at the beginning of the ACPI pilot is reported at the Massachusetts Institute of Technology's Center for Global Science website (http://puddle.mit.edu/~detlef/OSE/global.html). In the application of ocean data assimilation for this project, historical ocean observations were the basis for a four-dimensional history of the global ocean's physical properties for the period 1992-97.

This information was used to initialize the ocean component of a global climate model for anthropogenic signal prediction – a type of initialization that had never been done before. Prior to this project, simulations of anthropogenic climate change have used a variety of ways to spin up the ocean component of the coupled model, but they have all suffered from potential errors associated with the so-called "cold start" problem. This problem results from the memory time of the deep ocean, which is 100-500 years or more. Since the fluxes of heat, momentum and fresh water to the oceans are unknown for more than a few decades into the past, there is always a question as to whether the ocean component of a conventionally spun-up model is close enough to the true current ocean state. Initializing with observed data should greatly lessen this major uncertainty in simulating anthropogenic climate change. See Pierce et al. (this issue) for a more thorough discussion of the methods and results of Element 1.

Element 2: Modeling Anthropogenic Climate Change

The ocean data described above were used to initialize the coupled ocean/atmosphere/ice model (i.e., the PCM) used in this project. The so-called Business As Usual greenhouse gas emissions growth assumptions of the Intergovernmental Panel on Climate Change were used to force the PCM and generate the future climate-change scenarios used in this project. These emissions assume robust world-wide economic growth, continued wide-spread use of fossil fuels, rates of technological change (reflected in decreases in the energy intensity of the world economy) similar to that experienced over the past 50 years, but no adoption of aggressive policies for dealing with greenhouse gas emissions. Other assumptions could be made, but they would not materially affect the rates of climate change we will see over the next half-century. Details of the model may be found at the Parallel Climate Model website (http://www.cgd.ucar.edu/pcm/). Components of the PCM include the NCAR CCM3 atmospheric general circulation model (which in turn includes a land surface model and a river transport model), a parallel river transport model, the Los Alamos National Laboratory (LANL) Parallel Ocean Program (POP) model, and the LANL/University of Washington sea-ice model. The full PCM has been configured to run with a serial flux coupler that has been designed to perform the calculation of the components of the climate system as efficiently as possible on a variety of parallel high capacity supercomputers. The PCM is currently fully operational. Analyses of ongoing simulations have shown realistic amplitude El Niño, La Niña, North Atlantic and Pacific Oscillations, and Antarctic Circumpolar Wave properties in the simulations. The PCM uses no flux correction terms.

A list of PCM variables produced for this project can be found in the Guide to PCM project data (http://www.cgd.ucar.edu/pcm/PCMDI/). Dai et al. (this issue) summarizes the results of the PCM simulations performed for the ACPI Demonstration Project, and Zhu et al. (this issue) provides an evaluation of the performance of the PCM in simulating the current climate of the continental U.S. with an emphasis on variables that are particularly relevant for performing hydrologic assessments.

Element 3: Regional Downscaling and Impact Assessment

Although global-scale models can represent the large-scale features governing climate and climate change over an area like the western United States, they do not provide the kind of detail, and especially the spatial detail, needed to simulate hydrologic response. They also cannot represent the very important effects that complex, mountainous terrain has on local as well as regional climate variability. This latter effect is extremely important in correctly simulating spatial patterns of precipitation and snow-pack retention.

In order to provide this kind of detail, current global model simulations must be downscaled. Two types of downscaling were used. One type, called dynamic downscaling, used a regional-scale climate model, which was driven by boundary conditions supplied by the global model (Giorgi et al., 2001). The principal purpose of dynamical downscaling in the western U.S. was to improve representation of the effects of topography on climatic features, especially precipitation and snow pack. The second type of downscaling, statistical, uses statistical/empirical relationships to generate "weather" data at the temporal and spatial scales required by the hydrological models used in this project. Because of the very high spatial and temporal resolution required by hydrological models, statistical downscaling was applied to both the global-scale simulations and the dynamically downscaled data. The results of both approaches are compared in several of the papers in this issue.

Once appropriately downscaled, results from the three future climate scenarios produced by the PCM were used to assess the effects of these changes on hydrological response of major river basins in the western United States, as well as on some of their subbasins. Issues such as changes in basin snow pack, changes in the amounts and timing of river discharge, and on the ability of current dam and reservoir systems to adapt to the simulated changes and meet current water resource demands were examined. We also examined other issues such as changes in the availability of water for irrigated agriculture, changes in water quality and their implications for fish survival, and possible changes in the risks of large-scale forest fires.

The majority of papers included in this volume describe the results of Element 3 activities. Leung et al. report on dynamical downscaling of the three ensemble PCM simulations for a 20-year period of the mid-century, and Han and Rhodes discuss downscaling experiments using a different model. Wood et al. compare different approaches to statistically downscaling climate simulated by the PCM and a regional climate model for hydrologic applications. Hydrologic assessments of the Columbia River Basin, Sacramento-San Joaquin Basin, Colorado River Basin, and the western U.S. in general are presented by Payne et al., VanRheenen et al., Dettinger et al., Christensen et al., and Stewart et al., respectively. Knowles and Cayan discuss how changes in hydrology might affect the San Francisco Bay estuary and Sacramento Basin, while Pierce examines changes in biological activity in the North Pacific that could result from anthropogenic climate change. Brown et al. provide analyses of fire weather impacts, and Vail et al. examine the effects of mid-century climate change on water management in the Yakima River, an economically important tributary of the Columbia in Washington State.

Besides the papers that are collectively published in this special issue, Leung et al. (2002a,b,c) and Leung and Qian (2002) have investigated various aspects of dynamical downscaling based on simulations driven by global reanalyses for the western U.S. These papers indicate the value of downscaling in improving simulations of weather and climate features in regions of complex terrain.

Principal Results

The clearest change indicated by the climate-change simulations generated by this project is a general large-scale warming over the West – reaching an additional 1-2C, as compared to present, by the middle of the century. The most significant impact of this warming will be a large reduction in mountain snow pack and a commensurate reduction in natural water storage. The effects of global warming are already being seen in the West in terms of earlier melting of mountain snow packs and earlier dates for spring runoff (Dettinger et al. and Stewart et al., this issue). *What this work shows is that, even with a conservative climate mode, current demands on water resources in many parts of the West will not be met under future climate conditions – much less the demands of a larger population and a larger economy*. For example,

- Even by mid-century we see that The Colorado River Reservoir System will not be able to meet all of the demands placed on it, including water supply for Southern California and the inland Southwest, since reservoirs levels will be reduced by over one-third and releases by as much as 17 percent. The greatest effects will be on lower Colorado River basin states. All users of Colorado River hydroelectric power will be affected by lower reservoir levels and flows, which will result in reductions in hydropower generation by as much as 40 percent. Basically, we found the fully allocated Colorado system to be at the brink of failure, wherein virtually any reduction in precipitation over the Basin, either natural or anthropogenic, will lead to failure to meet mandated allocations.
- In the Central Valley of California, it will be impossible to meet current water system performance levels, so that impacts will be felt in reduced reliability of water supply deliveries, hydropower production and in-stream flows. With less fresh water available, the Sacramento Delta could experience a dramatic increase in salinity and subsequent ecosystem disruption.

- In the Columbia River System, residents and industries will likely be faced with the choice of water for summer and fall hydroelectric power or spring and summer releases for salmon runs, but not both. ACPI Demonstration Project research shows that with climate change, the river cannot be managed to accommodate them. In fact, the window for successful salmon production in the Pacific Northwest may become so compressed by climate change that some species could cease to exist regardless of any current or future water policies.
- In smaller, snowmelt-driven rivers, these changes will be larger. Many of these rivers, such as the Yakima River in Washington State, are important sources of water for irrigated agriculture. Less snow pack and earlier runoff will mean reduced ability to meet summer irrigation needs, higher water temperatures, and increased conflict between agricultural users and those whose principal concern is sustaining endangered fish populations.
- Finally, the increases in summer temperature and decreases in summer humidity indicated by the dynamically downscaled results of this research show a substantial increase in fire danger over much of the West. The most affected regions are the northern Rockies, Great Basin, and Southwest – regions already much affected by fire activity. By 2070, the length of the fire season could be increased by two to three weeks in these regions.

These results do not envision an easy future for users and managers of the West's water resources, but it is our contention that better information about this future will prepare us to do a better job in facing its challenges. The work presented in this volume certainly does not provide all the information needed. Future work will require the application of more than one global climate model in order to give a better indication of the range of climate futures facing this region of the country, especially since the projections provided by this "best case" model may be too conservative. Future work should also include active participation of decision-makers who can use this information to design actions that might reduce the vulnerability of water resources, and other climate-sensitive systems, to future climate changes. We also recognize that information on the range of climate futures and on details about these futures will improve as our models improve, but we believe that current information on the climate changes facing the West is sufficiently robust that it must begin to be taken seriously in decisions involving water resource planning, land use planning, and environmental protection or restoration. As one of our colleagues in this study has pointed out, the greatest risk in thinking about the future of climate-sensitive systems is to assume that the climate of the last century will be the climate we will face in the next.

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