2004

The Effects of Climate Change on Water Resources in the West: Introduction and Overview

Semtner, Bert

Kluwer Academic Publishers

Climatic Change 62: 1–11, 2004
http://hdl.handle.net/10945/48926

THE EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES IN THE WEST: INTRODUCTION AND OVERVIEW

TIM BARNETT [1], ROBERT MALONE [2], WILLIAM PENNELL [3], DETLET STAMMER [1], BERT SEMTNER [4] and WARREN WASHINGTON [5]

[1]*Scripps Institution of Oceanography, La Jolla, CA, U.S.A.*
[2]*Los Alamos National Laboratory, Los Alamos, NM, U.S.A.*
[3]*Pacific Northwest National Laboratory, Richland, WA, U.S.A.*
[4]*Naval Postgraduate School, Monterey, CA, U.S.A.*
[5]*National Center for Atmospheric Research, Boulder, CO, U.S.A.*

Abstract. The results of an experimental 'end to end' assessment of the effects of climate change on water resources in the western United States are described. The assessment focuses on the potential effects of climate change over the first half of the 21st century on the Columbia, Sacramento/San Joaquin, and Colorado river basins. The paper describes the methodology used for the assessment, and it summarizes the principal findings of the study. The strengths and weaknesses of this study are discussed, and suggestions are made for improving future climate change assessments.

In the summer of 2000, the U.S. 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. A second objective was 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 Initiative (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. 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 as follows:

Climatic Change **62:** 1–11, 2004.

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.

1. Project Implementation

The ACPI Demonstration Project was implemented as three distinct elements. These elements are depicted in Figure 1. The first element (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 project element (Element 3) downscaled these large-scale projections of the global model to ensembles of regional scale projections for the western United States. These projections were then used to estimate local impacts on wa-

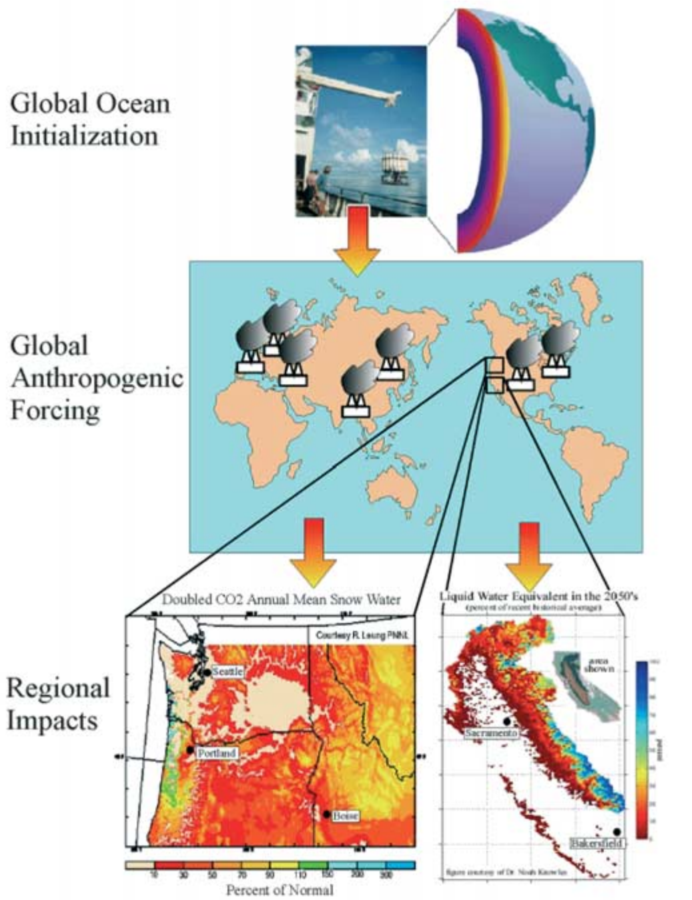

Figure 1. The Accelerated Climate Prediction Initiative Demonstration Project was implemented in three distinct elements. In Element 1, ocean observations were used to initialize a coupled ocean/atmosphere global climate model. In Element 2, this model was used to generate three distinct projections of future climate change for the 21st century. In Element 3, these global-scale projections were downscaled in order to provide improved representation of the effects of topography on the climate, and these downscaled data were used to examine the effects on various climate-sensitive environmental systems.

ter 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 Demonstration Project 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 of 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. (2004) 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, continued 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* (PCM) website (http://www.cgd.ucar.edu/pcm/), or the reader can refer to the paper by Dai et al. and its references for more information on the PCM. Components of the PCM include the following:

- The NCAR Community Climate Model version 3 (CCM3) atmospheric general circulation model (which in turn includes a land surface model),
- the Los Alamos National Laboratory (LANL) Parallel Ocean Program model, and
- the Naval Postgraduate School 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 of the 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. (2004) summarizes the results of the PCM simulations performed for the ACPI Demonstration Project, and Zhu et al. (2004) provides an evaluation of the performance of the PCM in simulating the current climate of the continental United States 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 snowpack 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 United States was to improve representation of the effects of topography on climatic features, especially precipitation and snowpack. 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 snowpack, in the amounts and timing of river discharge, and in 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 possible changes in the risks of large-scale forest fires and the possible effects of climate change on biological productivity in the north Pacific.

The majority of papers included in this volume describe the results of Element 3 activities. Leung et al. (2004) report on dynamical downscaling of the three ensemble PCM simulations for a 20-year period of the mid-century, Han and Roads (2004) discuss downscaling experiments using a different regional climate model model, and Mason (2004) describes a statistical downscaling technique. Wood et al. (2004) 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 United States in general are presented by Payne et al. (2004), VanRheenen et al. (2004), Dettinger et al. (2004), Christensen et al. (2004), and Stewart et al. (2004), respectively. Knowles and Cayan (2004) discuss how changes in hydrology might affect the San Francisco Bay estuary and Sacramento Basin, while Pierce (2004) examines changes in biological activity in the North Pacific that could result from anthropogenic climate change. Brown et al. (2004) provide analyses of fire weather impacts.

Besides the papers that are collectively published in this special issue, Leung et al. (2003a–c) and Leung and Qian (2003) have investigated various aspects of dynamical downscaling based on simulations driven by global reanalyses for the western United States, and Leung and Qian (2004) analyzed the ensemble regional climate change scenarios described in Leung et al. (this issue) for hydrologic impacts in the Georgia Basin/Puget Sound region. These papers indicate the value of downscaling in improving simulations of weather and climate features in regions of complex terrain.

2. Principal Results

The clearest change indicated by the climate-change simulations generated by this project is a general large-scale warming over the West: a warming that by the middle of the century reaches an additional 1–2 °C as compared to present. The most significant impact of this warming would be a large reduction in mountain snowpack 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 snowpacks and earlier dates for spring runoff (Dettinger et al., 2004; Stewart et al., 2004). *What this work shows is that, even with a conservative climate model,* current *demands on water resources in many parts of the West will not be met under plausible future climate conditions, much less the demands of a larger population and a larger economy*. For example, given the changes projected by the PCM in this study

- 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 reduced by as much as 17%. 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%. 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 the failure to meet mandated allocations.

- In the Central Valley of California, it will be impossible to meet current water system performance levels; 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 both. 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 snowpack 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. However, the work presented in this volume cannot be viewed as the final word on the problem. The global climate change projections that drive the conclusions of this study were generated by a model with fairly low climate sensitivity. Thus these projections, especially the projected temperature changes, might be viewed as a 'best case' scenario. Future work should involve application of more than one global climate model and downscaling models in order to give a better indication of the range of climate futures facing this region of the country. We also recognize that information on the range of climate futures, and details about these futures, will change and improve as our models improve. Nevertheless, we believe that current information about the climate challenges facing the West is sufficiently robust that it must be taken into account by those concerned about or responsible for managing water resources and other climate-sensitive systems. As one of the participants 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.

3. Suggestions for Future Work

This has been a unique study, but it is one likely to be repeated in the future. With this in mind, we offer some suggestions on how future work of this kind might be improved. These suggestions are listed below following the 'end-to-end' sequence of the paper.

1. Initialization of the ocean component of the coupled model, which had not been done before, is critical to getting the phase of the greenhouse signal properly. In our case, the time dependent evolution of the model's ocean temperature field fit the observations so well that we had little opportunity to see what kind of impact the initialization made on future predictions. This technique needs to be explored using other global models in order to assess its value.
2. The anthropogenic forcing assumptions that drove the PCM simulations in this study omitted some known pollutants or pollutant-effects, such as black carbon and the indirect effect of aerosols on cloud radiative properties that are thought to have significant impacts on climate. Clearly, these effects should be included in future studies.
3. The results of this study are contingent upon the accuracy by which the global model is able to project changes in the global scale circulation and scalar fields that affect regional climate. These scales have not been a particular focus of past model evaluation activities. The regional accuracy of the signal produced by a global model needs to be estimated and subjected to a rigorous regional detection and attribution analysis, and particular attention needs to be given to the sensitivity of regional climate simulations to the parameterization of cloud and boundary layer processes in both global and regional models.
4. The accuracy of the downscaling schemes has been addressed by Wood et al. (2004) by comparing the effects of using a combination of statistical and dynamical downscaling techniques on simulated snowpack and streamflow. Other evaluations of dynamical downscaling are described by Leung et al. (2003a–c; Leung and Qian, 2003); who compared various regional climate simulations driven by two sets of global reanalyses with observations. Future work should focus more on the use of skill score and regional detection and attribution to

characterize and determine the statistical significance of downscaled climate signals and affected variables such as streamflow.

5. As mentioned in the previous section, future assessments should employ more than one global model to estimate the regional signal that is used to drive the downscaling schemes. In the case of the PCM used in this study, its low climate sensitivity – compared to most other global climate models – gave us a conservative estimate of currently expected warming impacts. Other models will probably project a larger regional temperature change, and they may project changes in regional-scale precipitation patterns that were not seen in the PCM simulations. These differences could, in turn, lead to different impacts than we have found. Such model runs will need to be carried out in ensemble-mode; for as we found out in this study, the decadal variability can be large, and the use of ensemble simulations are particularly important for examining changes in extreme (low probability) events.
6. The entire end-to-end assessment procedure should be subjected to an end-to-end attribution analysis using current climate data. In this way, each step of the process, along with its results, can be compared with observations, thereby establishing confidence limits on the various predictions. In our case, the modeled global ocean signal successfully reproduced the last 50 years of observations (Barnett et al., 2001); and the hydrological models were able to simulate stream flow results for the last 50 years or so in a way that agreed well with observations (Woods et al., 2004; Stewart et al., 2004). However, each of these tests was done in stand-alone mode. In future studies, these assessments need to be serially linked in a consistent end-to-end attribution analysis in order to be more rigorous.

Acknowledgements

The Accelerated Climate Prediction Initiative (ACPI) Pilot effort was supported largely by the U.S. Department of Energy's Office of Science (BER) through numerous contracts and subcontracts to the participants. Most of the production runs of global and regional models were executed at the Center for Computational Sciences (CCS) at Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy. The San Diego Supercomputer Center provided dedicated machine resources for the crucial ocean initialization component of the ACPI Demonstration Project. These ocean data were provided by ECCO state estimation activity at SIO. Los Alamos National Laboratories provided computer resources for PCM runs, ECCO work, and additional feasibility tests associated with the ocean initialization. In addition to the U.S. Department of Energy, many of the participating organizations also supported the effort. These organizations include the Scripps Institution of Oceanography, the U.S. Geological Survey, U.S. Department of Defense, the National Center for Atmospheric Research, the University of Washington, and the U.S. Department of Energy's Pacific Northwest National Laboratory.

We also wish to acknowledge the useful comments and suggestions of an anonymous reviewer.

References

Barnett, T. P., Pierce, D. W., and Schnur, D.: 2001, 'Detection of Anthropogenic Climate Change in the Worlds Oceans', *Science* **292**, 270–274.

Brown, T., Hall, B., and Westerling, A.: 2004, 'The Impact of Twenty-First Century Climate Change on Wildland Fire Danger in the Western United States: An Applications Perspective', *Clim. Change* **62**, 365–388.

Christensen, N., Wood, A., Voisin, N., Lettenmaier, D., and Palmer, R.: 2004, 'Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin', *Clim. Change* **62**, 337–363.

Dai, A., Washington, W., Meehl, G., Bettge, T., and Strand, W.: 2004, 'The ACPI Climate Change Simulations', *Clim. Change* **62**, 29–43.

Dettinger, M., Cayan, D., Meyer, M., and Jeton, A.: 2004, 'Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099', *Clim. Change* **62**, 283–317.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., Von Storch, H., Whetton, P., Jones, R., Mearns, L., and Fu, C.: 2001, 'Regional Climate Information – Evaluation and Projections', *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*, Cambridge University Press, 881 pp.

Han, J. and Roads, J.: 2004, 'U.S. Climate Sensitivity Simulated with the NCEP Regional Spectral Model', *Clim. Change* **62**, 115–154.

Knowles, N. and Cayan, D.: 2004, 'Elevational Dependence of Projected Hydrologic Changes in the San Francisco Estuary and Watershed', *Clim. Change* **62**, 319–336.

Leung, L. R. and Qian, Y.: 2003, 'The Sensitivity of Precipitation and Snowpack Simulations to Model Resolution via Nesting in Regions of Complex Terrain', *J. Hydrometeorology*, in press.

Leung, L. R. and Qian, Y.: 2004, 'Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century', *Canadian Water Resources Journal*, submitted.

Leung, L. R., Qian, Y., and Bian, X.: 2003a, 'Hydroclimate of the Western United States Based on Observations and Regional Climate Simulation of 1981–2000. Part I: Seasonal Statistics', *J. Climate* **16**, 1892–1911.

Leung, L. R., Qian, Y., Bian, X., and Hunt, A.: 2003b, 'Hydroclimate of the Western United States Based on Observations and Regional Climate Simulation of 1981–2000. Part II: Mesoscale ENSO Anomalies', *J. Climate* **16**, 1912–1928.

Leung, L., Qian, Y., Bian, X., Washington, W., Han, J., and Roads, J.: 2004, 'Mid-Century Ensemble Regional Climate Change Scenarios for the Western United States', *Clim. Change* **62**, 75–113.

Leung, L. R., Qian, Y., Han, J., and Roads, J. O.: 2003c, 'Intercomparison of Global Reanalyses and Regional Simulations of Cold Season Water Budgets in the Western U.S.', *J. Hydrometeorology*, in press.

Mason, S.: 2004, 'Simulating Climate over Western North America Using Stochastic Weather Generators', *Clim. Change* **62**, 155–187.

National Assessment Report: 2000, *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States*, A Report of the National Water Assessment Group for the U.S. Global Change Research Program, 151 pp.

National Research Council: 1998, *Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities*, National Academy Press, Washington, D.C., 65 pp.

Payne, J., Wood, A., Hamlet, A., Palmer, R., and Lettenmaier, D. 2004. 'Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin', *Clim. Change* **62**, 233–256.

Pierce, D.: 2004, 'Future Changes in Biological Activity in the North Pacific due to Anthropogenic Forcing of the Physical Environment', *Clim. Change* **62**, 389–418.

Pierce, D., Barnett, T., Tokmakian, R., Semtner, A., Maltrud, M., Lysne, J., and Craid, A.: 2004, 'The ACPI Project, Element 1: Initializing a Coupled Climate Model from Observed Conditions', *Clim. Change* **62**, 13–18.

Stewart, I., Cayan, D., and Dettinger, M.: 2004, 'Changes in Snowmelt Runoff Timing in Western North America under a "Business as Usual" Climate Change Scenario', *Clim. Change* **62**, 217–232.

VanRheenen, N., Wood, A., Palmer, R., and Lettenmaier, D.: 2004, 'Potential Implications of PCM Climate Change Scenarios for Sacramento-San Joaquin River Basin Hydrology and Water Resources', *Clim. Change* **62**, 257–281.

Wood, A., Leung, L., Sridhar, V., and Lettenmaier, D.: 2004, 'Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs', *Clim. Change* **62**, 189–216.

Zhu, C., Pierce, D., Barnett, T., Wood, A., and Lettenmaier, D.: 2004, 'Evaluation of Hydrologically Relevant PCM Climate Variables and Large-Scale Variability over the Continental U.S.', *Clim. Change* **62**, 45–74.

(Received 9 July 2002; in revised form 28 July 2003)