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Protocols For Projects For Simulation Of Present And Future Climates In California

Authors
Duffy, Philip B.
Taylor, John A.
Taylor, Karl E.

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PROTOCOLS FOR PROJECTS FOR SIMULATION OF PRESENT AND FUTURE CLIMATES IN CALIFORNIA

PIER Project Report

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Public Interest Energy Research Program

Prepared By:
Philip B. Duffy, John A. Taylor, and Karl E. Taylor
Lawrence Livermore National Laboratory

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Prepared By:
Philip B. Duffy
John A. Taylor
Karl E. Taylor
Lawrence Livermore National Laboratory
Livermore, California 94550

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Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Guido Franco,
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead
Energy-Related Environmental Research

Ron Kukulka,
Acting Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert L. Therkelsen
Executive Director

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Protocol for the Intercomparison of Simulation of California's Climate, contract number 500-02-004, Work Authorization MR-023, by Philip B. Duffy, John A. Taylor, and Karl E. Taylor of the Lawrence Livermore National Laboratory.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

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Abstract

A pair of projects is presented with the goal of improving understanding of future climate change in California. The first project assesses the ability of regional climate models and statistical downscaling to simulate the present climate in the State. This will provide understanding of the strengths and weaknesses of competing models and approaches. The second project provides probabilistic projections of future climate for use by decision-makers, impacts researchers, and others. The uncertainties in these projections will reflect uncertainty in knowledge of future climate perturbations (e.g., greenhouse gas emissions) as well as uncertainty in the response of the climate system. For the first (present climate) project, three options are presented which differ in the level of funding required ($500,000 to $2 million) and in the quantity and quality of information expected to result. The future-climate project assumes the existence of present climate simulations, which are needed as baselines. Thus, this project assumes that one of the more comprehensive present-climate project options will have been completed.

1.0 Introduction

This section outlines the goals of the project, its study area/model domain and model resolution, its project and funding options, and coordination details.

1.1. Strategic Goals

- Provide planning agencies, impacts researchers, and policymakers with the highest quality information on climate change in California;
- generate climate scenarios that will become the standard scenarios for climate change planning in the State government;
- generate climate scenarios with enough temporal and geographic resolution to allow advanced climate change impact studies;
- provide researchers with a detailed analysis of how well their models reproduce observations, both in absolute terms and relative to other models, with the goal of developing better climate models;
- coordinate to the maximum extent possible with related efforts (e.g., the North American Regional Climate Change Assessment Program (NARCCAP), the Ouranos Consortium, and others) in order to avoid duplication of effort and ensure the maximum possible involvement by other researchers; and
- maximize return on sponsor's investment by facilitating analysis of simulations and relevant observations by researchers funded by others.

1.2. Technical Goals

- *Evaluate simulations of today's climate in California:* Assess the ability of regional climate models (RCMs) and statistical downscaling techniques to reproduce observations of today's climate in California. Assess the strengths and weaknesses of individual dynamical and statistical models, as well as the overall relative merits of dynamical vs. statistical approaches to downscaling.
- *Identify shortcomings in individual models:* Where possible, problems in the simulation results will be linked to specific shortcomings in the models (for example inadequate spatial resolution, poor representation of subgrid scale processes, etc.) This will point the way towards improved future models.
- *Evaluate simulations of the twentieth century*: Models which more accurately simulate observed trends in California's climate may make better projections of future climate in the State. For this reason, it will be useful to evaluate existing GCM simulations of the transient climate of the twentieth century in California. (These simulations use climate forcings—e.g., greenhouse gas concentrations—that change with time, in contrast to other simulations that use constant forcings representative of the present climate.) This evaluation will focus on how well different models reproduce observed twentieth-century climate trends in California. These trends will be identified in the California Energy Commission-funded project on "Detection and Attribution of Climate Change in California," to be performed at the University of California Merced and the National Center for Atmospheric Research (NCAR).

- *Make probabilistic projections of future climate in California*: These projections will be based on all participating groups simulating one or more common climate-change scenarios. Bayesian and other related techniques for optimally combining multiple projections will be investigated and applied. Quantitative estimates of uncertainties will be made. An assessment will be made of to what extent these uncertainties can be narrowed by developing an optimal weighting strategy that gives more weight to models which more accurately reproduce observations.
- *Identify robust aspects of predicted climate changes*: The disagreements among different climate models in predicted changes in California's climate have been documented by Coquard et al. (2004) and others. Despite these differences, aspects of predicted climate changes are robust in the sense of being common to most or all models. Identifying these robust aspects is an important aid to decision-makers.
- *Convert all simulation results into a common file format*: This is an important step in facilitating analysis by independent researchers and by policymakers; this in turn maximizes return on the sponsor's investment.
- *Make all project results and data publicly available*: Internet access to project data will facilitate analysis by the broader communities of climate researchers, impacts assessors, and decision-makers. Material to be made available will include simulation results, associated documentation, results of analyses funded by the California Energy Commission (Energy Commission), published reports and papers, and links to analyses performed by independently funded groups.

1.3. Study Area/Model Domain, and Model Resolution

The area of interest to the sponsor (the Public Interest Energy Research program of the California Energy Commission) is the state of California. The area of analysis will include the Pacific Northwest (because this region supplies hydropower to California), the Colorado River Basin (which supplies water to California) and parts of Nevada that supply water to California. The simulation domain for regional climate models (RCMs) will include these regions. All participating RCM groups will use the same model domain; this will simplify interpretation of results by eliminating one unnecessary difference among different modeling groups.

Because impacts of climate change on California's hydrological cycle are potentially important, the Energy Commission expects that simulations will be performed at sufficient spatial resolution to accurately simulate the hydrological cycle. Because mountain snow cover is an essential part of the hydrological cycle in California, this means that spatial resolutions sufficient to accurately represent the water content of mountain snow should be used. Recent research has shown that resolutions in the neighborhood of 40 kilometers (km) are not adequate for this purpose (Duffy et al. 2004). Thus, the Energy Commission's goal is for RCM groups to use 10-km resolution in California with coarser resolution, if needed, outside of California. In addition, some impacts studies require "transient" simulations in which climate evolves continuously from the present. In recognition of the great computational demands this imposes, the Energy Commission expects the lead contractor to provide participating RCM groups with at least some of the supercomputing resources needed to perform required simulations.

1.4. Multiple Projects and Funding Options

Below we describe separate projects dealing with: (1) evaluation of ability of RCMs and statistical downscaling methods to represent the present climate in California (i.e., a model evaluation project); (2) use of same RCM models as those in (1) and statistical downscaling techniques to make probabilistic projections of future climate. For the model evaluation (present-climate) project, we present plans for Basic, Intermediate, and Comprehensive project options, potentially receiving Energy Commission funding levels of $500K, $1M, and $2M, respectively. For the project on projections of future climate, we present one option with a total budget of $2M. The latter project, however, assumes that either the Intermediate or Comprehensive model evaluation project will have been previously completed.

1.5. Coordination

Coordination between related projects maximizes return on sponsors' investments, by eliminating duplication of effort and maximizing inter-comparability of results across different projects. Energy Commission-funded modeling studies of California will be coordinated with ongoing related projects, especially the North American Regional Climate Change Assessment Program (NARCCAP) under the direction of Linda Mearns at NCAR, and the Ouranos Consortium in Canada (Daniel Caya, Director). Coordination should include use of the same climate change emissions scenarios and time windows; and may include use of the same GCM scenario calculations as a starting point for downscaling. (At present NARCCAP is planning to the use NCAR-CCSM, the Canadian Climate Centre CGCM3, the Hadley Center HADCM3 and HadAM3, and the GFDL AOGCM). In addition, the Energy Commission's California studies could use as a starting point for downscaling high-resolution global "time-slice" simulations performed at ~50-km resolution for NARCCAP. This would allow the Energy Commission to leverage results of and investments in these other projects, and use of the same scenarios and GCMs would be automatic.

2.0 Project Organization

2.1. Hub and Spoke Structure

The project will be coordinated at a "hub" location, where staff will interact with the sponsor (PIER/Energy Commission) to ensure that the following project deliverables are completed on time:

- providing input (e.g., boundary condition) data to participating groups;
- providing some computer access to participating groups;
- assembling observational data needed for evaluation of simulations;
- developing techniques and metrics for evaluation of simulations;
- performing some analysis of simulation results;

- providing participating groups with tools for performing quality control on simulation results, and for converting simulation results into a common file format;
- assembling documentation on models and downscaling techniques used;
- making simulation results and documentation publicly available.

Participating ("spoke") simulation groups will be responsible for:

- providing computer time to perform required simulations (in some cases)
- performing agreed-upon simulations on time;
- performing quality control on simulation results (using tools supplied by the hub);
- converting simulation results into a common file format (using tools supplied by the hub);
- providing appropriate documentation for their simulations.

2.2. Funding of Participating Modeling Groups

Groups participating in global model intercomparison projects (e.g., the Atmospheric Model Intercomparison Project (AMIP), Coupled Model Intercomparison Project (CMIP), and Paleoclimate Modelling Intercomparison Project (PMIP)) have traditionally not been compensated for the cost of performing and submitting simulations. In some cases, however, free computer access was provided. This philosophy, including supplying computer time, is followed in the Basic model evaluation project described below. In the higher-cost projects, however, the workload for participating RCM groups will be much greater, because of the larger number of simulations required. (These differences are quantified in Appendix 1. The statistical downscaling work does not present the same problem because of the relatively low computational burden afforded by this technique.)

To prevent lack of support from being a barrier to participation, and to help ensure that results are provided in a timely manner, we therefore recommend at least partial support for effort costs of a limited number of selected dynamical and statistical downscaling groups in these higher-cost projects. Groups to be funded will be selected by the Hub contractor, with final approval from the Energy Commission. Any dynamical or statistical downscaling groups willing to participate *gratis* will be encouraged to do so.

2.3. Computer Access

As discussed above, the Energy Commission's goal is for RCM simulations for this project to be performed at 10-km resolution. (Resolution in this ballpark is needed to accurately represent the hydrological cycle in California.) This requirement creates very significant computational demands for participating RCM groups. To help meet these requirements, the Hub contractor will provide participating groups with limited access to a large, shared computer. (This was done in the initial stage of the AMIP project.) This will have the additional benefit of concentrating the large volume of model output in one location, and thus minimizing the need to move large quantities of data. For the higher-cost model intercomparison projects, the cumulative computational needs of all participating groups will probably exceed what any Hub contractor can provide. Therefore for these project options, participating groups will be expected to supply their own computing to the maximum extent possible, and will be expected to demonstrate ability to do this before receiving funding from the Energy Commission.

2.4. Relevant PIER/Energy Commission-funded Activities

The Energy Commission's Public Interest Energy Research (PIER) program is investing significant resources in research activities at the Scripps Institution of Oceanography (SIO) that can be described in general terms as climate monitoring, analysis, and modeling. SIO and the Desert Research Institute (DRI) are installing meteorological and hydrological stations in remote high elevations and in important transects in the state. The data, however, may not be ready for this intercomparison work, but it will be useful for future intercomparisons to be conducted in about six years. The climate analysis work being done by SIO could guide the effort designed to select the global climate models best-suited for the California region. For example, there may be little hope for global models that do not properly capture historical El Niño events (in the statistical sense) because of the importance of this mode of variability for California (Wigley 2004).

The SIO and the Western Regional Climate Center (WRCC) have developed a California Climate Data Archive website (http://www.calclim.dri.edu) that eventually will make long-term climate data easily available to state agencies, utilities, and researchers. This effort should facilitate the preparation of historical gridded data for comparison with dynamic model outputs or specific stations for statistical models.

Under funding from PIER, SIO is also evaluating and enhancing their dynamic and statistical downscaling techniques. Regarding dynamical modeling, SIO is using the Regional Spectral Model (RSM) at 10-km resolution for a climate reanalysis of the United States and California regions for the last 50 years. In the near future, SIO will investigate the effects on climate of changes of vegetation and of land use changes (e.g., increased urbanization) in California again simulating conditions in the last 50 years. With respect to statistical techniques, SIO is enhancing a weather generator and a canonical correlation method to allow for statistical downscaling of GCM outputs (Gershunov and Cayan 2003). These methods will allow the efficient and low-cost downscaling to numerous GCM outputs as suggested by Tom Wigley in a discussion paper prepared for PIER (Wigley, 2004).

The SIO is also calibrating/enhancing a statewide hydrological model that will be used to generate the hydrological outputs needed to drive the water system models being enhanced under separate funding for PIER.

Phil Duffy, Ben Santer, and Tom Wigley are under contract with PIER to conduct a preliminary climate change detection and attribution study for the California region. This study may prove useful to the intercomparison effort.

Mark Jacobson from Stanford is conducting an exploratory study of the role of aerosols on climate in California. Results of this study to date are available at www.energy.ca.gov/pier/final_project_reports/CEC-500-2005-003.html.

Similarly, Daniel Rosenfeld and his team from the Hebrew University of Jerusalem is investigating the role of aerosols on precipitation levels in high elevation in California, because his preliminary analysis suggests that aerosols may be diminishing the precipitation -enhancing orographic effect in the State.

Finally, PIER is providing very limited support to dynamic regional climate modeling groups at the University of California (UC) Santa Cruz (Lisa Sloan), UC Davis (Bryan Weare), and Lawrence Berkeley National Laboratory (Norm Miller).

3.0 Basic Model Evaluation Project ($500K)

3.1. Project Scope

This minimum-cost project option would focus on evaluation and intercomparison of statistical and dynamical downscaling approaches as applied to California. To most clearly identify the strengths and weaknesses in the competing downscaled solutions, an observationally based, large-scale solution would be used as the starting point for downscaling. (This approach will minimize the extent to which defects in the large-scale solution—e.g., in lateral boundary conditions supplied to RCMs and statistical downscaling groups—create errors (which could be misattributed to the downscaling methodologies themselves) in the downscaled solutions. Thus, this project would use an atmospheric "reanalysis" (a model product created by assimilating the maximum possible number of observations into a climate model) as the starting point for downscaling. Simulations from (free-running) global climate models (GCMs) would not be downscaled in this project option.

3.2. Technical Approach

As explained above, this project would evaluate how well different downscaling approaches and models can reproduce the present climate in California. The starting point for downscaling would be the European Centre for Medium-Range Weather Forecasting's "ERA 40" reanalysis. This choice of reanalysis is dictated by the Energy Commission's desire for dynamical models to simulate California using a grid size of 10 km or thereabouts. (This spatial resolution is needed to adequately simulate California's hydrological cycle.) Bertrand Denis et al. (2002) showed that problems result if the resolution "jump" (ratio of grid sizes) between the driving and nested models is much greater than around 12. Thus, if we wish nested models to use 10-km resolution, the grid size in the driving large-scale solution (in this case reanalysis) should not greatly exceed 120 km. This rules out the use of traditional coarse-resolution reanalyses, and suggests that the ERA 40 reanalysis, at T159 truncation (~85 km resolution), should be well-suited for our purpose. An additional advantage of using the ERA 40 reanalysis is that its spatial resolution closely matches the resolution (75 km, or T170 truncation) of the global atmospheric model which would be downscaled in the more comprehensive model intercomparison projects. This means that conclusions drawn from evaluation of downscaled reanalysis are more likely to apply also to downscaled GCM results.

To meet budget constraints, this project option would not develop new evaluation methodologies, or new software tools for model evaluation. Again, to meet budget constraints, this option would explicitly pay for only minimal analysis of simulation results. To maximize return on the sponsor's investment, analysis by third parties would be facilitated by converting all model results to a common file format, and by making all model results and appropriate documentation publicly available.

3.3. Specific Tasks

- Prepare and distribute input data for downscaling (atmospheric reanalysis, etc.) to participating downscaling groups (Hub)
- Simulate the present climate in California by downscaling from reanalysis (Spokes)
- Put downscaling results into a common file format (Hub)
- Gather relevant observational data (Hub)
- Perform basic evaluation of downscaling results vs. observations and reanalysis (Hub)
- Make downscaling results, appropriate documentation, relevant observational data (or links thereto), and evaluation results publicly available (Hub)

3.4. Roles and Responsibilities

Senior staff at the Hub location would be responsible for:

- overall project coordination;
- interactions with the sponsor (PIER/Energy Commission) and with Spoke participants;
- meeting reporting obligations to the sponsor (e.g., reports and meetings);
- determine appropriate methods for evaluating downscaled solutions; and
- coordination of a peer-reviewed publication.

Technical staff at the Hub location would:

- prepare input data (reanalysis, etc.) and distribute them to Spoke participants;
- prepare software for conversion of simulation results to a common file format;
- convert results of downscaling into a common file format;
- gather observational data for evaluation of downscaled solutions;
- perform evaluation of downscaled solutions; and
- establish a project Web site that will make simulation results, documentation, relevant observational data, and results of simulation evaluations publicly available.

Staff at Spoke locations would be responsible for:

- producing a downscaled version of present climate in California using large-scale input data provided by the Hub; and
- contributing to a peer-reviewed publication.

The tables below list effort levels and costs associated with each project task. For purposes of estimating costs, effort costs are assumed to be $200K/yr for senior staff and $150K/yr for technical staff. These effort breakdowns, cost rates, and project budgets are not meant to be rigidly adhered to; rather, they are shown to provide some reassurance that the project's scope of work is appropriate to the overall funding available.

	Year 1	Year 2
Hub	Prepare and distribute large-scale representation of atmospheric state (reanalysis). Gather observational data for model evaluation.	Evaluate downscaling results by comparing to observations. Make all downscaling results publicly available.
Spokes	Simulate present climate in California by downscaling reanalysis.	Put downscaling results into standard file format.

Table 1: Outline of tasks to be performed at Hub and Spoke locations

	Task	Effort level senior staff (mos)	Effort level technical staff (mos)	Est'd Cost (Year 1; $K)
Hub	Prepare and distribute reanalysis dataset	0	2	25
	Gather observational data for model evaluation	0.5	2	33
	Develop software for conversion of simulation results to common file format	0	1	13
	Coordinate project coordination; interact with the sponsor, etc.	1	0	17
Total Hub		1.5	5	88
Each Spoke	Simulate present climate in California by downscaling reanalysis	0	0	0
Total each Spoke		0	0	0
Total all Spokes		0	0	0
Total Hub + Spokes		1.5	5	**88**

Table 2: Detailed effort breakdown for Year 1 of the Basic model evaluation project. Effort costs are assumed to be $200K/yr for senior staff and $150K/yr for technical staff. Table shows effort levels and costs for each spoke location; bottom rows shows total costs, assuming that there are three spoke locations.

	Task	Effort level senior staff (mos)	Effort Level technical staff (mos)	Est'd Cost (Year 2; $K)
Hub	Evaluate downscaling results vs. reanalysis and observations.	0	6	75
	Establish project Web site.	1.5	1.5	44
	Prepare a peer-reviewed publication.	2	1	46
	Archive downscaling results and make them publicly available.	0	0.5	6
	Project coordination; interaction with the sponsor, etc.	1	0	17
Total Hub		3.5	8.75	188
Spokes	Preparation of peer-reviewed publication	1	1	29
Total each spoke		1	1	29
Total all Spokes		3	3	88
Total Hub + Spokes		6.5	11.75	**275**

Table 3: Detailed effort breakdown for Year 2 of Basic model evaluation project. Effort costs are assumed to be $200K/yr for senior staff and $150K/yr for technical staff. The table shows effort levels and costs for each spoke location; bottom rows shows total costs assuming there are three spoke locations.

	Year 1 ($K)	**Year 2** ($K)	**Total** ($K)
Effort at Hub	88	188	275
Effort at all Spokes	0	88	88
Computer access	40	40	80
Data storage	4	0	4
Travel/workshops	20	20	40
Publications	0	20	20
Total	**152**	**355**	**507**

Table 4: Estimated overall project budget for Basic model evaluation project.

4.0 Intermediate Model Evaluation Project ($1 million)

4.1. Project Scope

This option includes everything in the Basic Option, as well as the following:

(1) Downscaling the solutions of two (free-running) global climate models, in addition to downscaling reanalysis. This would allow us to understand how well downscaling methods can reproduce the present climate when starting from large-scale solutions that may contain significant errors. The two GCMs would be selected from among those that have performed IPCC scenario simulations with 6-hourly output saved. In addition, the two GCMs should have significantly different responses to climate change within the study area.

(2) Additional analysis activities: development and application of new metrics (figures of merit) and tools for evaluation of high-resolution regional simulations (as distinct from approaches commonly used to evaluate coarse-resolution global simulations). Along with simulation results and observations, these tools would be made publicly available to facilitate analysis of project results by third parties.

4.2. Downscaling Methodology

This project and the Comprehensive Intercomparison Project described below would use the same two-step downscaling process that was used successfully in the European PRUDENCE project. In Step 1, results of a coarse-resolution coupled ocean/atmosphere/sea ice model are downscaled using a high-resolution global atmospheric model. This is accomplished by forcing the atmospheric model with sea-surface temperatures (SSTs) and sea-ice concentrations from the coarse-resolution coupled model. For these simulations, an atmospheric model resolution of ~75 km (corresponding to T170 truncation in a spectral model) is recommended. In Step 2, results of the high-resolution global atmospheric model are further downscaled using a nested regional climate model (RCM) or statistical downscaling approach. For these simulations, the Energy Commission is recommending an RCM resolution of 10 km.

This approach has several advantages. First, a large majority of coarse-resolution coupled model simulations cannot be downscaled directly using nested RCMs, because the needed 6-hourly or 12-hourly boundary data is usually not saved. By contrast, the 2-step downscaling process described above requires only monthly SST and sea ice data, which are always saved. Thus, this process allows us to select any coarse-resolution GCM simulation, rather than the small minority that save driving boundary data, for downscaling. Second, the approach recommended above allows the use of higher resolution in the nested RCM. As discussed above, Denis et al. (2002) found that grid size ratios (GCM:RCM) exceeding 12:1 create numerical problems in the downscaled solution. Thus, GCM simulations at T42 truncation (~300-km grid size; typical of GCMs) should not be directly downscaled to finer than ~25 km resolution. By contrast, if we first downscale a coarse-resolution coupled model with a global atmospheric model at T170 truncation (~75-km resolution), this could in principle house a nested model at a resolution as fine as ~6 km. Third, and most importantly, the fidelity of the downscaled solution is likely to be superior in the two-step downscaling approach, because in this approach the RCM or statistical model receives higher-resolution boundary data—which should be more free of biases—than when directly downscaling a coarse-resolution model.

Results obtained recently at LLNL show that this two-step downscaling approach can produce impressive simulations of California's climate (see Figure 1). The high fidelity of these simulations results from fine spatial resolution used in the RCM (which results in good representation of topographically driven climate features) and fine resolution in the driving GCM (which results in relatively bias-free driving boundary conditions).

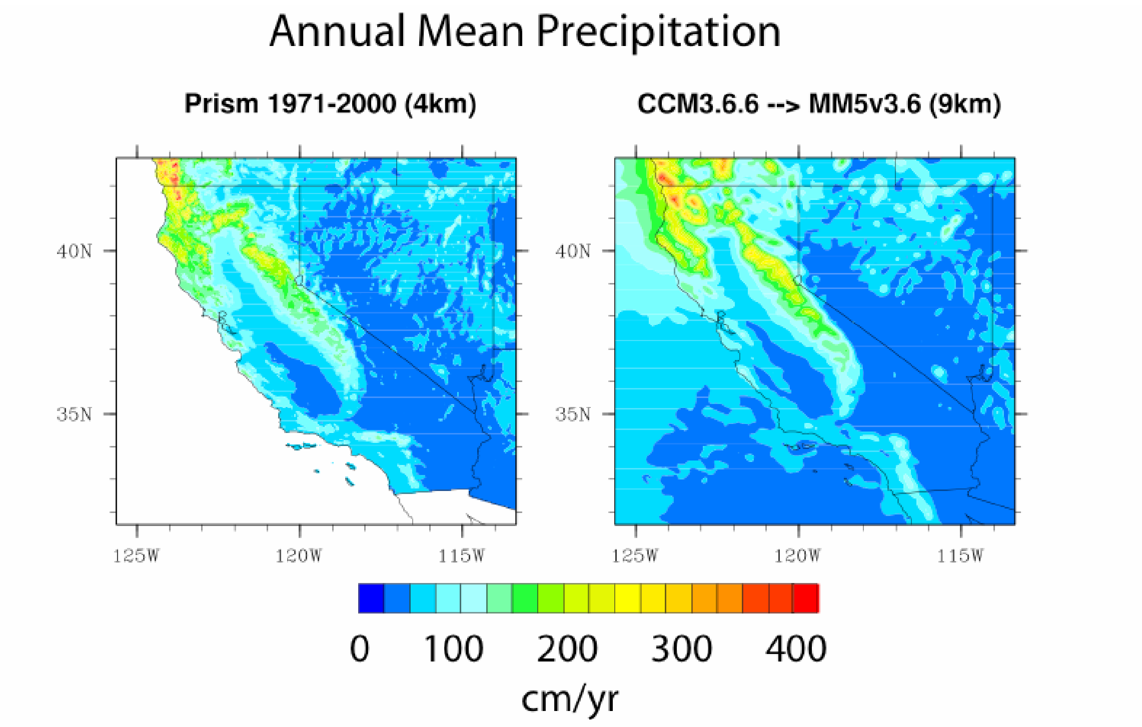

Figure 1. **Right:** Annual-mean precipitation in California and Nevada, simulated at LLNL by the MM5 RCM run at 9-km resolution, driven with lateral boundary condition data from the CCM3 GCM run at T170 truncation (~75-km resolution). **Left:** An observation-based estimate of precipitation, based on station and radar data interpolated using a PRISM physically based interpolation methodology.

4.3. Specific Tasks

This option would include all tasks from the Basic Option, plus the following:

- Simulation of present-climate in California by downscaling present-climate-simulations from two GCMs (Spokes);
- Additional evaluation of present climate simulations, including evaluation of ability to simulate variability on a range of time scales (Hub).

	Task	Effort level senior staff (mos)	Effort level technical staff (mos)	Est'd Cost (Year 1; $K)
Hub	Prepare and distribute large-scale representation of atmosphere (reanalysis + 2 GCMs)	0	3	38
	Gather observational data for model evaluation	0.5	2	33
	Develop software for conversion of simulation results to common file format	0	1	13
	Coordinate project; interact with the sponsor, etc.	3	0	50
Total Hub		3.5	6	133
Each Spoke	Simulate present climate in California by downscaling reanalysis + 2 GCMs	1	3	54
Total each Spoke		1	3	54
Total all spokes		5	15	271
Total Hub + Spokes		8.5	21	**296**

Table 6: Detailed effort breakdown for Year 1 of the Intermediate model evaluation project. Effort costs are assumed to be $200K/yr for senior staff and $150K/yr for technical staff. The table shows effort levels and costs for each spoke location; bottom rows shows total costs, assuming there are five spoke locations.

	Task	Effort level senior staff (mos)	Effort Level technical staff (mos)	Est'd Cost (Year 2; $K)
Hub	Evaluate downscaling results vs. observations.	2	12	183
	Establish project Web site.	2	3	71
	Prepare peer-reviewed publication	3	2	75
	Archive downscaling results and make them publicly available.	0	1	13
	Coordinate project; interact with the sponsor, etc.	1	0	0
Total Hub		8	18	358
Spokes	Prepare peer-reviewed publication.	1	1	29
Total each spoke		1	1	29
Total all Spokes		5	5	146
Total Hub + Spokes		13	23	446

Table 7: Detailed effort breakdown for Year 2 of the Intermediate model evaluation project. Table shows effort levels and costs for each spoke location; bottom rows shows total costs, assuming there are 5 spoke locations.

	Year 1 ($K)	**Year 2** ($K)	**Total** ($K)
Effort at Hub	133	358	492
Effort at all Spokes	271	146	417
Computer access	35	35	70
Data storage	35	35	70
Travel/workshops	20	20	40
Publications	0	20	20
Total	**494**	**614**	**1,108**

Table 8: Estimated overall project budget for Intermediate model evaluation project.

5.0 Comprehensive Model Evaluation Project ($2 million)

5.1. Project Scope

This option would provide the most comprehensive evaluation of techniques for simulating California's climate. This option would include everything in the Intermediate project, with additional research activities such as those listed below. Research activities may include a special focus on the hydrological cycle. Each of these activities would be performed by the Hub contractor and one or more selected Spokes, with the intention that each Spoke would participate in at least one activity.

Effect of spectral nudging on RCM solution: In the spectral nudging approach, the downscaled RCM solution is "nudged" or restored towards the large-scale driving solution on large spatial scales only. (i.e., the fine-scale features in the RCM solution are unmolested.) Use of this approach is based on the assumption that the large-scale features in the downscaled solution cannot be more realistic than those in the large-scale driving solution. (If this assumption is wrong, then the nudging worsens the downscaled solution.) This approach is controversial, because high-resolution topographic forcing can in principle improve the downscaled solution relative to the large-scale driving solution, even on the large scale. This is particularly likely in a region like California, where the climate is strongly influenced by topographic variations. We would evaluate the effect of spectral nudging on the fidelity of the simulated climate in California.

Sensitivity to spatial resolution of large-scale solution: The sensitivity to spatial resolution of the large-scale driving solution would be investigated. There are two possible ways to do this: (1) use boundary conditions from a GCM run at multiple resolutions (here the finer resolution solutions should be more accurate on the large scale, as well as more detailed); or (2) use boundary conditions at different resolutions created by low-pass filtering one fine-resolution solution (here the finer-resolution solutions would be more detailed—but not more accurate on the large scale—than the coarse-resolution solutions.)

Effect of spatial resolution of regional climate model: The effects of increased RCM resolution on the realism of downscaled present-climate simulations would be investigated. Evaluation would include variables relevant to the hydrological cycle.

Regional vs. global reanalysis: Relative realism of downscaled solutions using global vs. regional reanalysis would be investigated. This further evaluates effects of resolution of global model output on realism of downscaled solutions.

Dynamical vs. statistical downscaling: The ability of statistical vs. dynamical downscaling approaches to simulate the present climate in California would be explicitly analyzed. Competing downscaling approaches would start from the same large-scale solution (coarsened reanalysis).

Expanded Web portal: The Web site would be expanded with the goal of becoming the "portal" for facilitating the analysis of climate change on California. This will include a comprehensive set of links to information and analysis tools relevant to climate change in California.

Besides including the above research activities, this project option would include downscaling of one additional GCM. Thus, the first year's activities would include downscaling of 1 reanalysis and 3 GCMs.

This project's budget would also permit downscaling of results from additional GCMs. These could be chosen specifically for their ability to simulate climate in California. Criteria for selecting GCMs may include:

- the ability to realistically simulate ENSO;
- no flux adjustments;
- realistic on-shore moisture fluxes from the Pacific ocean;
- adequate simulation of anthropogenic warming of Pacific Ocean;
- a realistic simulation of twentieth-century trends in the Western United States; and
- a realistic treatment of aerosols.

	Task	**Effort level senior staff (mos)**	**Effort level technical staff (mos)**	**Est'd Cost (Year 1; $K)**
Hub	Select GCMs to be downscaled	2	2	58
	Prepare and distribute large-scale solutions from reanalysis and 3 GCMs	0	4	50
	Gather observational data for evaluation	0.5	2	33
	Develop software for conversion of simulation results to common file format	0	1	13
	Coordinate project; interact with the sponsor, etc.	2	0	33
Total Hub		2.5	7	188
Each Spoke	Simulate present climate in California by downscaling reanalysis + 3 GCMs	1	3	54
Total each Spoke		1	3	54
Total all spokes		5	15	271
Total Hub + Spokes		7.5	22	458

Table 9: Year 1 effort budget for the Comprehensive model evaluation project.

	Task	Effort level senior staff (mos)	Effort Level technical staff (mos)	Est'd Cost (Year 2; $K)
Hub	Evaluate downscaling results vs. observations.	3	16	250
	Establish project Web site.	2	4	83
	Prepare peer-reviewed publications.	5	3	121
	Put downscaling results into standard file format.	0	2	25
	Coordinate project; interact with the sponsor, etc.	2	0	0
Total Hub		12	25	513
Spokes	Prepare peer-reviewed publication.	4	2	92
Total each spoke		4	2	92
Total all Spokes		20	10	458
Total Hub + Spokes		32	35	788

Table 10: Year 2 effort budget for the Comprehensive model evaluation project.

Task	Sr. staff effort level (mos)	Sr. staff effort cost ($K)	Tech staff effort level (mos)	Tech staff effort cost ($K)	Total effort cost ($K)	Hardware cost ($K)	Total Cost ($K)
Effect of spatial resolution of global climate model	2	33	4	50	83	10	93
Effect of spatial resolution of regional climate model	2	33	4	50	83	10	93
Regional vs. global reanalysis	2	33	4	67	100	10	110
Dynamical vs. statistical downscaling	2	33	4	67	100		100
Expanded Web portal	1	17	4	67	83	30	113
Total	9	150	20	300	450	60	510

Table 11: Year 3 effort budget for the Comprehensive model evaluation project.

	Year 1 ($K)	Year 2 ($K)	Year 3 ($K)	Total ($K)
Effort at Hub	188	513	225	925
Effort at all Spokes	271	458	225	954
Computer access	35	35	0	70
Data storage	97	0	60	157
Travel/workshops	20	20	0	40
Publications	0	20	0	20
Total	**610**	**1,046**	**510**	**2,166**

Table 12: Overall project budget for the Comprehensive model evaluation project.

6.0 Project for Probabilistic Projections of Future Climate

6.1. Project Scope

This project will be funded independently of the model intercomparison projects described above, and will build on their results. Specifically, however, this project assumes prior completion of either the Intermediate or Comprehensive model evaluation project; this level is needed to provide baseline present-climate information for comparison to future-climate projections. In contrast to the above model evaluation projects, which focus on simulating the present climate, the goal of this project will be to make probabilistic projections of future climate in the study area. "Probabilistic projections" means projections that explicitly account for uncertainties in: (1) future climate forcings (e.g., greenhouse gas emissions), and (2) uncertainties in scientific understanding of how the climate system will respond to these forcings. In practical terms, this means that this project will: (1) consider multiple future climate scenarios (i.e., multiple possibilities for future greenhouse gas concentrations and other climate perturbations); and (2) consider results from multiple climate models. It may also be useful to explore uncertainties with respect to parameter values within individual models.

An essential part of the project will be the selection and application of techniques for estimating uncertainties in future climate (i.e., for making probabilistic projections) based on multiple simulations. Multiple techniques for estimating uncertainties should be investigated. For example, the technique of Bayesian Model Averaging (BMA) has been used to make probabilistic forecasts of river flows (e.g., Rasmussen, 2001) and daily-timescale weather (Raftery et al., 2003), and in diverse fields such as epidemiology (Viallefont et al., 2001) and econometrics (Bates and Granger, 1969). Nonetheless, the BMA approach has only recently been applied to climate prediction (e.g., Tebaldi et al., 2004). This project will explore its use with regional climate models. In BMA, a projection is made from results of multiple models by calculating a weighted average; the weights are based on how well each model can reproduce relevant observations. The information needed to obtain these weights will be obtained from the Intermediate or Comprehensive model intercomparison project described above. BMA produces both a mean model result and an associated uncertainty.

In addition to combining results of multiple models into probabilistic projections, techniques for estimating uncertainties with respect to parameter values within individual models will be developed and applied. Because of the great computational demands of climate models, uncertainties in the results with respect to values of internal parameters are typically explored minimally, if at all. Yet these uncertainties may be very significant; in addition, more careful optimization of parameter values should allow a more realistic model solution. Assuming an adequate level of project funding, intelligent algorithms for exploring parameter space within individual climate models will be applied and evaluated.

This project will directly leverage the model intercomparison project described above in that it will use “control” (present-climate) simulations from that project (assuming that project is funded at the Intermediate or Comprehensive level). Effects of increased greenhouse gases and other climate perturbations will be measured in terms of differences between those control simulations and future-climate simulations to be performed under this project.

6.2. Selection of Scenarios, Models, and Time Windows

Projecting future climate in California requires selections of: (1) emissions scenarios for greenhouse gases and other perturbing agents, (2) global climate models to be downscaled; (3) time window(s) to be analyzed. These choices will be made primarily with the goal of maximizing coordination with related projects, especially NCAR’s North American Regional Climate Change Assessment Program (NARCCAP). This project has tentatively selected the A2 SRES scenario (a relatively high-emission scenario, with CO_2 concentrations increasing monotonically to 850 ppm in 2100). This scenario will be simulated using four GCMs; these GCM simulations will be downscaled by five different RCMs. The tentative choice of time window of interest to NARCCAP is 2040–2100. The project described here will also consider a time window centered on 2030, for the purpose of providing climate change projections to be used in the DWR’s 2008 Water Plan. In addition, this project will also consider a more moderate emissions scenario, such as the IPCC SRES B1 (a 550 ppm stabilization scenario). The Hub contractor, in consultation with the sponsor, should be free to reconsider these choices if future developments warrant (in particular, in order to maintain coordination with related projects). It may be desirable, in addition to greenhouse gas and other atmospheric forcings, to consider one scenario including regional land-use change.

6.3. El Niño/Southern Oscillation

Climate variability in California on a year-to year timescale results primarily from the El Niño/Southern Oscillation (ENSO). As a result, ENSO has significant societal impacts in California. Because of the regional importance of ENSO, it is important that this project use models that accurately represent ENSO and its regional manifestations (e.g., precipitation anomalies). Unfortunately, however, there is no consensus as to how increasing greenhouse gases will affect ENSO—its amplitude, frequency, or regional manifestations (e.g., Meehl et al., 1993; Knutson et al., 1997; Collins, 2000). Therefore, in order to assess possible impacts of ENSO in California in future altered climates, this project will first examine the behavior of ENSO in IPCC simulations of the twenty-first century. The intermodel range of changes in ENSO amplitude and frequency will be assessed, as will the inter-model range in regional temperature and precipitation responses. Simulations that represent the range of credible ENSO responses will be downscaled either statistically or dynamically. This will yield a suite of regional simulations that span the range of possible future behavior of ENSO.

6.4. Project Organization

Like the model intercomparison projects described above, this project will use a Hub and Spoke organization. The Hub is responsible for overall project coordination, data management, data analysis, etc., while the spoke groups perform regional simulations with their individual models or downscaling approaches. Also, as with the model intercomparison projects, the Hub location will provide some computer access to participating downscaling groups.

6.5. Specific Activities

- Identify which future climate scenarios to be considered (Hub).
- Examine future behavior of ENSO in IPCC twenty-first century simulations (Hub or selected Spoke).
- Obtain global model results for future climate scenarios to be used as the basis for downscaling; global model results with 6-hourly time resolution are needed (Hub).
- Prepare GCM results for use as starting point for downscaling (Hub).
- Downscale future climate scenarios using multiple RCMs and/or statistical downscaling approaches. (Spokes)
- Combine multiple downscaled solutions into a probabilistic projection using Bayesian Model Averaging. (Hub)
- Investigate climate uncertainties due to uncertainties in parameter values with one RCM. (One selected Spoke, working with Hub)
- Establish project Web site making available all model results, documentation, and probabilistic projections (Hub).

	Year 1	Year 2	Year 3
Hub	Obtain, prepare, and distribute large-scale future-climate solutions from 2 GCMs, for 2 scenarios Establish project Web site	Combine multiple downscaled solutions into a probabilistic projection using Bayesian Model Averaging Update project Web site, making initial project results publicly available	Investigate sensitivities to parameter values within one RCM Update project Web site to include latest and all project results
Spokes	Downscale 4 future climate simulations (2 GCMs, 2 scenarios)	Put downscaling results into standard file format.	Investigate sensitivities to parameter values within one RCM (one Spoke only)

Table 13: Outline of tasks to be performed at Hub and Spoke locations for the probabilistic projections of future climate

	Task	Effort level senior staff (mos)	Effort level technical staff (mos)	Est'd Cost (Year 1; $K)
Hub	Prepare and distribute large-scale solution (2 GCMs, 2 scenarios)	0	4	50
	Establish project Web site	1	1	29
	Coordinate project; interact with the sponsor, etc.	2	0	33
	Select/develop method for producing probabilistic forecasts	1	12	167
Total Hub		4	17	279
Each Spoke	Downscale 4 future climate scenarios (2 GCMs x 2 scenarios)	1	4	67
Total each Spoke		1	4	67
Total all spokes		5	20	333
Total Hub + Spokes		9	37	613

Table 14: Detailed effort budget for Year 1 of the Future Climate Project

	Task	Effort level senior staff (mos)	Effort Level technical staff (mos)	Est'd Cost (Year 2; $K)
Hub	Combine projections into probabilistic forecast	3	12	200
	Update project Web site	1	3	54
	Prepare a peer-reviewed publication	4	2	92
	Project coordination; interaction with sponsor, etc.	1	0	0
Total Hub		9	17	363
Spokes	Put downscaling results into standard file format.	0	2	25
	Prepare a peer-reviewed publication	2	1	46
Total each spoke		2	1	46
Total all Spokes		10	5	229
Total Hub + Spokes		19	22	500

Table 15: Detailed effort budget for Year 2 of the Future Climate Project

	Task	Effort level senior staff (mos)	Effort Level technical staff (mos)	Est'd Cost (Year 2; $K)
Hub	Investigate sensitivity to RCM parameter values	3	12	200
	Update project Web site.	1	3	54
	Prepare a peer-reviewed publications	4	2	92
	Coordinate project; interact with the sponsor, etc.	1	0	0
Total Hub		9	17	363
Selected Spoke	Investigate sensitivity to RCM parameter values	3	5	113
	Prepare a peer-reviewed publication	2	1	46
Total selected spoke		5	6	158
Total Hub + Spokes		14	23	521

Table 16: Detailed effort budget for Year 3 of the Future Climate Project

	Year 1 ($K)	Year 2 ($K)	Year 3 ($K)	Total ($K)
Effort at Hub	279	363	363	1,004
Effort at all Spokes	333	229	158	721
Computer access	35	0	0	35
Data storage	28	125	0	153
Travel/workshops	20	20	20	60
Publications	0	20	20	40
Total	**696**	**757**	**561**	**2,013**

Table 17: Overall budget for the Future Climate Project

7.0 Summary of Annual Budgets

	Basic Intercomparison Project ($K)	Intermediate Intercomparison Project ($K)	Comprehensive Intercomparison Project ($K)	Future Climate Projections ($K)
Effort at hub	275	492	925	1,004
Effort at Spokes	88	417	954	721
Computer access	80	70	70	35
Data storage	4	70	157	153
Travel/workshops	40	40	40	60
Publications	20	20	20	40
Total	**507**	**1,108**	**2,166**	**2,013**

Table 18: Summary of annual project budgets for all of the projects

8.0 References

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Appendix A: RCM Workload, Data Volume, and Disk Cost

The table below lists total number of years to be simulated and volumes of data to be produced by RCM simulations for each project option.

	Low	Medium	High	Future
# GCMs to be downscaled	0	2	3	2
# RCMs	3	5	5	5
# Sims per RCM for each GCM	1	2	3	2
Length of each simulation	20	20	30	20
# reanalyses to be downscaled	1	1	1	0
Total # yrs simulated	60	500	1385	400
# RCM grid cells x direction	200	200	200	200
# RCM grid cells y direction	200	200	200	200
# RCM grid cells z direction	20	20	20	20
total #RCM grid cells	800000	800000	800000	800000
# RCM quantities stored	20	20	20	20
how often stored/yr	365	365	365	365
# numbers stored	3.504E+11	2.92E+12	8.0884E+12	2.336E+12
total data volume (Tbyte)	2.8	23.4	64.7	18.7
Disk cost ($K)	$4.2	$35.0	$97.1	$28.0

Estimated data volume from RCM simulations, and cost of associated disk space.

Appendix B: Bias Corrections and Simulation Evaluation Criteria

Dynamical models of regional climate (i.e., RCMs) require input data that are physically self-consistent. Temperature, pressure, and circulation fields, for example, must all be consistent with governing primitive equations. Thus, for dynamical downscaling, *ad hoc* correction of biases in the driving large-scale fields will lead to spurious results (or worse) in the RCM solution. For statistical downscaling, bias correction is feasible and may be desirable. Whether and how to perform bias corrections will be left to the individual statistical downscaling groups to decide.

Evaluation of downscaled climates will be based primarily on comparison to relevant observation-based data (including reanalyses). Comparison to observations will emphasize meteorological quantities of which observations of good quantity and quality are available, and also quantities having high societal impacts. Near-surface temperature, precipitation, and snow cover are especially important. Evaluation will involve assessment of monthly- and seasonal means, as well as interannual variability, especially response to ENSO.

Appendix C: List of Acronyms

AMIP	Atmospheric Model Intercomparison Project
BMA	Bayesian Model Averaging
CMIP	Coupled Model Intercomparison Project
DRI	Desert Research Institute
DWR	California Department of Water Resources
GCM	Global Climate Model (or General Circulation Model)
IPCC	Intergovernmental Panel on Climate Change
MIP	Model Intercomparison Project
NARCCAP	North American Regional Climate Change assessment Program
NCAR	National Center for Atmospheric Research
PIER	Public Interest Energy Research
PNNL	Pacific Northwest National Laboratory
PRUDENCE	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects
PMIP	Paleoclimate Modelling Intercomparison Project
RCM	Regional Climate Model
PIRCS	Project for Intercomparison of Regional Climate Simulations
SIO	Scripps Institution of Oceanography (U.C. San Diego)
SRES	Special Report on Emissions Scenarios (by the IPCC)
WRCC	Western Regional Climate Center