A Review of the Report *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy*

CONSULTANT REPORT

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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 (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 six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for Contract number 500-01-007, Work Authorization 36-AB-01, conducted by Michael Hanemann of the University of California at Berkeley, and Margaret S. Torn, of the Lawrence Berkeley National Laboratory. The report is entitled *A Review of the Report Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* This project contributes to the PIER Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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Executive Summary

Under contract to the PIER Environmental Area (PIER-EA), the Electric Power Research Institute (EPRI) managed a multiyear study that examined the potential effects of global climate change on California and prepared a report entitled *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy*. In view of the broad scope of this study and its importance for environmental policy in California, PIER-EA decided to solicit an expert review of the report to identify its strengths, limitations, and implications for future research.

Objectives

The reviewers examined each of the component analyses of the study, evaluating methods, data issues, conclusions, significance, and implications for future work on climate change impacts in California.

Outcomes

This research identified the strengths and limitations of the various efforts detailed in the EPRI report. The conclusions, recommendations, and benefits to California are discussed below.

Conclusions, Recommendations, and Benefits to California

The reviewers concluded that the study constitutes a significant step forward in the analysis of regional climate change impacts in the United States. At the same time, in recognition of the nascent state of climate impact science, they suggest that the study's findings be viewed not as specific predictions, but as a sensitivity analysis that considers a range of potential outcomes. In keeping with this view, they suggest that a high priority for future research should be the expanded and explicit consideration of uncertainty in both regional climate scenarios and specific categories of climate change impacts.

Following is a summary of other key recommendations:

- Create a set of official California climate projections incorporating regional specificity, stochastic information (such as temperature and precipitation variability), and additional relevant variables.
- Develop an integration and synthesis framework for analyzing impact interactions among sectors and for formulating coordinated, adaptive policy responses.
- Support or, as appropriate, exploit developments in dynamic vegetation modeling to reduce uncertainties regarding transient responses (among other factors), and to improve the representations of a range of bio-physical and relevant climatic effects.
- Include sub-regional specific detail and climatic variability effects in the analysis of coastal impacts.
- Extend public health impact analysis by incorporating more general and flexible representations of variance in incidence modeling and by including a broader range of potential impacts drivers.
- Explicitly incorporate uncertainty into urban growth projections.
- For the modeling of climate change impacts on energy demand:

1. Obtain the data resources needed to:
    a) disaggregate the energy composite used in this study,
    b) capture long-run trends from time series rather than cross-sectional observations, and
    c) incorporate explicit models of heating-and-cooling degree days in order to estimate climate change impacts.
2. Develop and estimate new econometric models drawing on these data and reanalyze welfare effects, including improved treatment of long versus short-run elasticities.
    - Experiment with alternative estimators besides ordinary least square in econometric models of climate change impacts on crop yield, and seek to obtain more disaggregated data.
    - Develop and apply non-optimizing models of climate change impacts on California water supply and demand, complementary to the optimizing model used in this study, in order to more accurately gauge substitution possibilities and adjustment frictions.

The implementation of these recommendations would produce improved California-focused climate change research and would benefit California through more accurate climate change information that the State's decision makers can use to design and implement informed policies.

Abstract

Climate change has the potential to affect many aspects of California—the survival of its unique ecosystems, its ability to produce electricity, the natural resources that support its economy, its supply of water and agricultural products, and the health of its citizens. This effort evaluated the PIER-funded studies that examined the potential impacts from climate change on these sectors, to create a knowledge base for research on climate change impacts in California and to identify paths and priorities for future research.

The researchers found that those studies provided an invaluable benchmark for future research on regional climate change impacts, both in California and elsewhere. Simultaneously, they emphasize that the studies' findings be viewed not as specific predictions of future climate and impacts, but as a sensitivity analysis that considers a range of potential outcomes. The reviewers provide a series of recommendations for future studies on climate change impacts in California, involving extensions and improvements in data, methods, and modeling techniques.

1.0 Introduction

The California Energy Commission, through its Public Interest Energy Research (PIER) Program, funded a valuable and comprehensive study of the potential impacts of climate change on California's ecosystems and natural resource sectors. This study represents a significant step forward in the analysis of potential regional impacts of climate change, and can serve as a benchmark not only for further work on California but for parallel efforts in other U.S. regions. It is particularly timely given the increasing attention to potential regional impacts among policy-makers at the national level and the corresponding efforts to refocus federally funded research toward this type of analysis.

2.0 Project Approach

The purpose of this review is several-fold. Given both the complexity of the issues and the fact that, inevitably, a study of this type raises as many questions as it answers, we address both the specifics of the analysis and its implications for further research. Accordingly, general comments on the overall research and on sector-specific findings and approaches are combined with remarks on study strengths and weaknesses, our views of how to interpret research findings, and recommendations for future research. We should emphasize that, in a number of cases, certain limitations of this analysis were a consequence of intentional constraints on its scope, and our comments should not be construed as criticisms of omissions by the study's authors.

3.0 Project Outcomes

3.1. Global Climate Change and California

In conceiving and implementing this study, the PIER program asked the researchers to take a proactive approach to understanding the impacts of global climate change across multiple resource sectors. We believe this investigation should be considered a dynamic process, and the current report used to define protocols and approaches that may be updated as model or database improvements become available. This framework will make it easier for California to keep pace with scientific advances in the study of global climate change and its impacts. In recognition of the nascent state of climate impact science, we suggest that the study's findings be viewed not as specific predictions, but as a sensitivity analysis that considers a range of potential outcomes.

3.2. Climate Scenarios

An obvious strength of this exercise was to analyze climate change impacts using the same climate scenarios for different sectors. This consistent approach enables results from one sector to be used as input to the impact study of another sector, to compare impacts across different sectors.

The assessment used a set of climate scenarios that represented the range of predicted changes in California temperature and precipitation under elevated levels of carbon dioxide,[1] spanning from "hot-wet" to "warm-dry." (These are also referred to as "warm-wet" and "cool-dry,"

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[1] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix II

respectively, in some chapters.) For future impacts assessments, the key areas for advances in the climate scenarios include: (1) greater spatial and temporal specificity, and (2) multiyear climate patterns, such as the El Niño-Southern Oscillation (ENSO) that strongly influences California's climate.

3.2.1. The Importance of Regional and Temporal Specificity

Many important disturbance processes, such as fire and flooding, operate over smaller areas than Global Climate Models (GCMs) resolve and shorter durations than they report. The timing of climate anomalies within the annual cycle is also important in this respect. For example, a few days of very hot, dry conditions would be much less likely to lead to fire if they occur in the spring than in autumn, when fuel loading is highest and many fuels are dead or already dry. With the exception of river flows, extreme events were not within the scope of this analysis. It is an important omission (as the authors of the study recognize) because changes in small-scale disturbances could lead to qualitatively different results in potential vegetation and in vegetation–climate feedbacks. It is possible that this could, in part, be accounted for by the inclusion of a "hot-dry" scenario in future modeling efforts. Another useful addition would be short-duration climate variables (i.e., wind and humidity) based on GCM output.

The need for greater regional and temporal specificity is further illustrated by comparing the impacts of the two "hot-wet" scenarios, Hadley CM2 and incremental T5P30. Even though the statewide average changes were the same for both scenarios (5°C warming, with a 30% increase in precipitation), there were qualitatively different impacts for agricultural yield and biodiversity index modeled with the two scenarios. The difference in impacts arises because of the regional and seasonal differences in precipitation modeled by the Hadley and incremental approaches.

3.2.2. Changes in Semi- to Multi-decadal Events

California's strong climatic link to the ENSO make it particularly vulnerable to the vagaries of this climate phenomenon. Most long-term California residents can recall the intense rainfall, mudslides, coastal destruction, and flooding that accompanied the unusually intense El Niño events of 1982–83 and 1997–98. El Niño recurrence also affects natural-resource-based industries (e.g., agriculture, fisheries, and tourism), government services (e.g., erosion control and water supply), and ecosystem processes and services (e.g., water quality and forest health). Both statistical and modeling evidence suggest that global climate change will alter the frequency and/or intensity of ENSO, although no scientific consensus exists concerning the magnitude or direction of that change. Similarly, other multi-decadal oscillations, such as the Pacific Decadal Oscillation (PDO), may take on greater significance to California's climate as the global climate changes.

3.2.3. Recommendations Concerning Climate Change Scenarios

To go out on a limb, we suggest that the State consider establishing a standard, official suite of climate change scenarios for California. This strategy would allow state actors to incorporate climate change considerations into their mandates. The State should still pursue a sensitivity analysis approach to establish a range of potential impacts. However, for the purpose of moving forward on climate change preparedness, we believe a "best guess" official set of climate change scenarios will be invaluable. Without standardized climate scenarios it will be difficult, if not impossible, for many sectors to incorporate climate change concerns into their

planning and operation. For example, all parties would have to consider the same climate change scenarios to have meaningful inclusion of climate change impacts into their planning processes.

The most useful set of scenarios would ideally have four attributes. They would: (1) be regionally specific, (2) represent a wet and dry case (or other appropriate range of uncertainty); (3) provide results with high temporal and spatial resolution and transient conditions, and (4) include regionally relevant climate variables and value-added climate products, such as wind, length of growing season, frost-free days and changes in Photosynthetically Active Radiation. To be a practical tool for a wide range of agencies, we also urge that the scenarios be distributed with technical assistance, and have an established protocol for updates. The PIER program's pursuit of protocols for downscaling GCM output and assessing its uncertainty are appropriate steps to build the capacity of generating and evaluating scenarios for statewide application.

3.3. Interactions Among Sectors

In considering the potential climate change impacts to a broad set of natural resource sectors and to California ecosystems, this study was remarkably comprehensive. Our main recommendations address ways the PIER Program could better capitalize on the work that has already been completed, and on how to approach future research more realistically and for ease of comparison across sectors.

Primarily, we think that attempts to summarize and synthesize this work would be justified in discussing some of the linkages among sectors even where there was not an explicit study of how one sector affects another. From a technical standpoint, one might consider how the post hoc or proactive responses in one sector would alter the choices available to other sectors. For example, does this study provide information to consider the impacts of changed water flows and dam management on aquatic habitats, or on energy supply? There are multiple demands on our natural resources, requiring that sectors which draw on the same resource must effectively communicate and collaborate in determining response priorities and tradeoffs.

In terms of the analysis framework, few of the studies considered proactive, adaptive mechanisms in a realistic manner. One exception was the sea level rise chapter, which examined a case of building sea walls preemptively. For the water markets (CALVIN-based modeling), there was proactive action, but as described below, it is unrealistically proactive. More generally, however, adaptive responses to climate change in the face of uncertainty need to be better incorporated into impact projections. After all, given what we know from these studies, we might act differently than they assumed, which could lead to very different projected impacts.

Some studies examined changes in water policy, some had market adaptation, some new technologies. Yet, no studies considered actions resulting from public policy, regulatory, or education responses to climate change. We suggest that a consistent framework, composed of a broad suite of potential adaptive tools, be applied across sectors. One relatively simple thing to do would be to make a table of sector scenarios for each study. This exercise may also help state agencies to explore the range of options available to them, and to further their understanding of the risks and tradeoffs associated with each option both within and among sectors.

From a comparative perspective, interpretation of responses across sectors was complicated by the fact that different sector studies employed different kinds and degrees of adaptive mechanisms. Tables in the report placed the monetary costs and benefits for one sector next to those from another sector, even when the underlying scenarios were not comparable. For example, the agricultural scenarios included technological innovation; whereas, the energy scenarios did not. The comparison of dollar costs gives the impression that cross-sector evaluations were comparing apples with apples, when in fact they were not. Because of this confusion, it was difficult to tease out, for example, that there was no climate change *ceteris paribus* scenario for the California water management studies (i.e., no analysis scenario in which the only substantive change was climate), and that there was no simulation of any year before 2010—the climate change scenario incorporates optimistic assumptions regarding the extent to which there is full resolution of legal controversies together with market optimization of water rights by 2020.

We suggest that the Energy Commission use more intrinsically based indicators in addition to tabulating projected impacts in terms of dollars. For example, potential indicators could include: percent change in sustainable timber yield, percent increase in public health services provided, or percent increase in personnel required for public land management. We also suggest that future work provide some range of uncertainty around point estimates of impacts, together with some discussion of the factors underlying this uncertainty and influencing the magnitude of the range of uncertainty. A consideration of uncertainty bands is especially important when comparing the consequences of alternative climate, CO_2, technology, or market scenarios.

3.4. Impacts on Terrestrial Vegetation

The healthy functioning of ecosystems is fundamental for the maintenance of ecosystem goods and services across many resource sectors, including maintenance of biodiversity, forest health and productivity, watershed protection and the quantity and quality of water supplied for human and in-stream uses. In this study, climate change impacts to terrestrial vegetation were simulated with the dynamic vegetation model, MC1-DGVM.[2] The results of the simulations were evaluated for vegetation distribution, productivity, and carbon storage. The results were also used as input to analyses of timber markets, biodiversity, and urbanization.

The modeling approach undertaken by Lenihan and Neilson makes several advances in predicting climate change impacts to terrestrial vegetation. An additional strength of this approach is that is considers vegetation changes in light of changes in land use. These results were used effectively to provide scenarios for several other sectors of the study. It was also interesting and valuable to compare the effect of projected new development with that of new plant community distributions.

MC1-DGVM simulates the effect of climate change on both the distribution of terrestrial communities and their carbon exchange. Because these phenomena respond to climatic changes on different timescales and according to different processes, the model comprises two

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[2] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix IV

interacting sub-models that simulate biogeochemistry and biogeography. The advantage of this approach is that the simulations were able to represent vegetation responses to changing environmental conditions, such as the effect of increased water use efficiency and drought stress on community composition, as well as on the rate of primary productivity by the extant community.

The MC1-DGVM makes advances by incorporating important ecosystem processes that are not included in most models. One particularly important process that appears in the model is a climate-sensitive fire regime. This feature is sophisticated in that fire behavior and outcome respond to direct factors (the effect of climate on fuel conditions and fire spread rate), as well as to indirect factors (the long-term effect of climate on fuel type and fuel loading). Moreover, modeled fire outcomes capture the effect of vegetation architecture and burning conditions on the amount of biomass burned in crown and ground levels.

The study found that climate change might cause large changes in California's vegetation distribution. The model predicts extensive changes in the distribution of vegetation communities and an increase of approximately 10% in ecosystem carbon stocks statewide.

As dramatic as these changes would be, the model may be underestimating the dislocation of plant species and overestimating carbon storage. As with nearly all existing dynamic vegetation models, the main structural compromises of this modeling approach are in the treatment (or lack thereof) of vegetation community transitions.

The inference that there is an overestimate of carbon storage and productivity in these simulations derives from the model's protocols for transition between one vegetation community and another. In these simulations, carbon exchange and growth of vegetation structures respond to climate, and cause changes in vegetation structure, biomass, and productivity. If those changes are large enough, the vegetation is reclassified as a new community type. Thus, the land surface adjusts to new climatic conditions by transitioning to a new vegetation community smoothly and gradually. Except for fire, there is no mortality. A de facto assumption is that the most suitable community type for the contemporary climate of a location is always present.

In reality of course, community transitions occur over decades or longer. In many cases, disturbance or mortality are required to create light gaps before new species can become established. In other cases, degradation of the standing vegetation occurs such that invading species can out compete others and become established (where degradation means decreased productivity, reduced reproductive success, and decreased competitive ability). Species and community assemblages may not be able to keep up with climate change (i.e., always be present in the location of most suitable climate) due to plant physiological limitations and anthropogenic barriers to migration. Therefore, the model is likely predicting that vegetation transitions will be more rapid or complete than is realistic and underestimating the amount of time (or area) covered by vegetation that is in a degraded condition or growing outside of its favored climate range.

Because the model does not incorporate disease or degradation, it probably overestimates state-wide productivity. Mainly the overestimate results from the model's failure to simulate (except for burned areas) patches of lowered productivity and carbon stock due to a mismatch between extant vegetation and new climatic conditions. Because there are no gaps except those created by fire, the simulations underestimate gaps, and thus overestimate the amount of vegetation

cover statewide and its total carbon storage. Appendix XV of the report gives a more detailed description of ecological processes that are not fully represented in current simulations of climate change impacts.

In the report, CO_2 fertilization was found to have a significant effect on projected productivity and carbon storage. For example, in the dry (PCM) scenario, the amount of new carbon sequestered was mainly dependent on the CO_2 effect. The PCM simulation projected a 28 teragram (Tg) C increase in C stock with climate change alone and a 78 Tg C increase if the scenario had elevated CO_2 concentration. In other words, of the total increase in ecosystem C stock, only 35% of the increase occurred in the scenario without elevated CO_2. Although sizeable, this effect is smaller than would be predicted by other dynamic vegetation models. Another model, MC1, employs a more conservative algorithm for CO_2 response, prescribing less improvement in water use efficiency and growth than does almost any model. Thus, for MC1, and even more so for other models, how ecosystems will respond to elevated atmospheric CO_2 concentrations is a major uncertainty. Without understanding the complex physiological and biogeochemical effects of elevated CO_2, it is not possible to predict by how much and for how long CO_2 fertilization will stimulate plant growth, or if down-regulation will occur. Moreover, it is not clear where nutrient limitations, such as nitrogen limitation, will impose new constraints on plant growth.

Table 1. The Effect Of Climate Change On Ecosystem Carbon Stocks With And Without Elevated CO_2 Levels.

Climate Scenario	Carbon Stock By Climate Scenario w/o Elevated Co_2	Carbon Stock By Climate Scenario w/Elevated Co_2	Increased C Due To Climate Change w/o Elevated Co_2	Increased C Due To Climate Change w/ Elevated Co_2
Historical Climate	445	461		
HadCM2 Climate Change	514	568 (10% more C storage than from climate alone)	69	107 (The change in C stock is 35% greater w / elevated CO_2 compared to climate change alone)
PCM Climate Change	473	539 (14% more C storage than from climate alone)	28	78 (The change in C stock is 65% greater w / elevated CO_2 compared to climate change alone)

3.5. Research Needs for Dynamic Vegetation Modeling

Relative to climate modeling, the field of dynamic vegetation modeling is still early in its development, with far fewer resources invested in model development, model comparison, or computing power. In addition, the development of dynamic vegetation models is hampered by a fundamental lack of understanding about the mechanisms that drive shifts in vegetation distribution and mortality. As a result, dynamic vegetation modeling approaches have structural compromises and simplifications. For example, models simulate vegetation functional groups or community types rather than species. Moreover, they generally omit any lag time for dispersal or migration, and thus most models predict overly rapid replacement of one vegetation community by another.

Probably the biggest uncertainly in modeling transient responses (i.e., to rapid climate change) is the lack of scientific understanding about what controls changes in species distribution on decadal to century time scales. For example, understanding what processes will drive species' removal, replacements, and range expansion. We do not know if the main causes of mortality or degradation will be direct physiological stress or if they will be mediated by disease, disturbance, invasion, or competitive exclusion. We also do not know when or if replacement of one species with another will be due to mortality or competition.

Range shifts and recolonization will depend upon the rate of dispersal or migration of species. Paleontological data suggest that during periods of climate change in the past, individual

species' ranges changed slowly, and at different rates, so that whole plant communities did not remain intact, but rather, formed new, transient community assemblages. Other uncertainties include understanding where and when soil development will limit vegetation shifts or productivity, and the role of plant pollinators. Pollinators are essential for specific reproduction and agricultural production of many species, but their potential response to climate change is poorly understood. There is a need for better understanding of how climate change may affect the processes that control the distribution and severity of diseases, pests, and pathogens and the development of better ways of characterizing disturbance in models.

The picture is especially complicated in California, where vegetation change may be influenced by multiple environmental changes, including urbanization, biological invasion, and pollution. For example, the large numbers of exotic invasive plants in California could result in new patterns of recolonization if they can out compete native colonizers after disturbance under changing climatic conditions. This possibility may be especially true if climate change increases the degree and frequency of disturbances, opening large areas to biological invasion.

Although scientific understanding is a key limitation, it is also true that, in many ways, models have not taken advantage of existing empirical and theoretical findings. After more than 25 years of government-sponsored research on the effects of elevated CO_2 and climate change, there is a wealth of data on ecosystem effects of global change. A major challenge for the next five years is to create a pipeline to move empirical results into models. In some cases, this activity is already happening. For example, the next generation of MC1-DGVM will incorporate processes of plant competition and seedling establishment. However, a greater attempt to incorporate research findings into models is certainly warranted. An equal challenge is to design the new experiments needed to fill the major gaps in dynamic vegetation models.

The dynamic vegetation modeling community has not been forced to the same level of inter-comparison as the climate models. In fact, there are some tests of the intrinsically transient and stochastic responses that remain out of reach of existing experimental capability.

Shaw (2003) developed a research roadmap for the ecological impacts of climate change in California. Its near-term research priorities provide an effective summation of the preceding arguments on what is needed for ecosystems and climate modeling, including: establish baseline data; develop more accurate and higher resolution regional climate models, incorporate more drivers into DVMs, and develop experimental designs to inform models. The key drivers not adequately addressed by the current generation of DVMs, were: land use, age structure of vegetation, dispersal rates and modes, invasive species; substrate types, transient states, disturbance regimes, migration corridors, and physiological responses to elevated CO_2.

3.6. Biodiversity

A major challenge for conservation organizations is to decide where preserves should be located to protect species in the future, and what new types of conservation arrangements could augment those preserves. Neilson and Lenihan predict significant change in vegetation communities, and thus, in suitable habitats for many species. It is hoped that these kinds of results can help guide conservation efforts—by illustrating that habitat distributions may change rapidly and continuously. Conservation planners should realize that it is not possible to pinpoint the location of suitable habitat in the next 100 years, and that no currently considered emissions scenario will stabilize in time to keep the habitat where it will be in the year 2100. An essential land preservation strategy is to protect a range of sites spanning the likely suitable

climate/ecosystem space that will occur over the next century. Promoting modes of development that can provide habitat and conservation value is also crucial. This study can help evaluate whether our current conservation areas are sufficient and how much bigger reserves need to be to accommodate uncertainty the future conditions.

Overlaying projected urbanization on the new vegetation distribution maps reveals that only a few small areas were left of the sage habitat, between the threats of climate change and development.[3] We make one note about the comparison of climate change impacts with urbanization. The direct comparison of the threat to biodiversity posed by climate change and urbanization is problematic because what was actually evaluated was land conversion. Urbanization is much more than land conversion alone. Conventional urbanization entails increases in air pollution, barriers to migration, introduced species, introduced predators like cats, roads (the primary cause of death for the endangered San Joaquin kit fox pup is road kill), and people (90% of wildfire starts in California are anthropogenic, so more roads and people means more starts in more places). In addition, land conversion causes fragmentation and thus degrades remaining unconverted areas.

In addition to studies of dominant vegetation types,[4] California's priorities for biodiversity research should concentrate on water-dependent habitats. Wetlands, riparian, and in-stream habitats should be a priority for future climate change research. These are among the state's rarest, most valuable, and most vulnerable habitats. We have converted or destroyed a bigger fraction of these habitats than any other in the state, they support more threatened and endangered species than other habitats, and they provide a disproportionate share of ecosystem goods and services. And all of them are directly vulnerable to changes in precipitation and hydrologic regime.

3.7. The Cumulative Impact of Multiple Global Changes

Lastly, it is important to remember that climatic changes will occur in concert with a number of other environmental changes. These include biological invasion, altered patterns of disturbance, urbanization, suburban sprawl, wetland destruction, deforestation, water and air pollution, elevated CO_2, and nitrogen deposition, among others. The overall effect of these cumulative changes may yield results to economic sectors and ecosystems that are qualitatively different from responses expected from climate change alone. For example, a number of single species, modeling, and ecosystem studies indicate that when plants are grown in an environment of elevated CO_2, net primary production (NPP) increases. Yet, when annual California grasslands were simultaneously exposed to elevated CO_2 with one or a combination of elevated temperature, increased rainfall, and simulated nitrogen deposition, elevated CO_2 was found to reduce NPP in comparison with control plots or to dampen the effect on NPP of the other treatments.

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[3] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix V

[4] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix VI

To give another example, plant pests and pathogens have seriously impacted many California plant species. Plant pathogens of vital concern today include *Phytophthora ramorum*, the fungus responsible for Sudden Oak Death; and the glassy-winged sharpshooter, which spreads Pierce's disease in grapes and threatens California's wine industry. The spread of plant pathogens could potentially interact with climate change in both harmful and beneficial ways. Climate change can ameliorate the environment for plant (as well as human) pathogens, causing them to spread more rapidly, or it could impede their spread. Plants that find themselves in stressful environments after climatic change occurs could also exhibit increased vulnerability to disease.

3.8. Timber Markets

The timber analysis employed an appropriate application of the MC1-DGVM (dynamic vegetation model) to forest type and growth rate. Unlike the general application of MC1-DGVM described above, for the timber study forest type was changed only after a disturbance by fire or logging. The forest community that was replanted matched the current year's vegetation range map that was output by MC1-DGVM; in other words the vegetation community that was replanted after disturbance was determined by the new climate conditions. The growth rate and biomass increment were modeled dynamically according to the current climate conditions and physiological parameters for the extant community.[5]

The most striking aspect of the timber study is the degree to which the scale of analysis governs the results. The major economic effect was caused by changes in global—rather than statewide—timber markets. Of course, the global estimates are highly uncertain: given the panoply of governments and government responses, cultures and cultural responses, ecosystem types, landscapes, and regional climate patterns that control global forest productivity, species mix, harvest rate, wood demand, and prices. The assessment does not report any kind of error bars of uncertainty estimate, so it is pointed out here that the results should be viewed as a potential sensitivity analysis and not as a prediction. Nevertheless, the exercise demonstrates the high sensitivity of a California commodity market to the global market.

The second aspect of scale is the consideration of California impacts statewide or on a regional basis. The state aggregate figures can disguise regional benefits and impacts. Mendelsohn estimates a $14 billion benefit to consumers statewide and $1 billion in losses to the timber producers. The benefits go to the areas of rapid development (wood use), like Southern California. The losses go to the rural counties. The report states that the rural and timber producing regions get about 5% of the benefit, which is $ 0.7 billion. If the timber-producing region absorbs all the loss ascribed to produces, then the timber-producing region suffers a loss of $0.3 billion (5% of $14 billion benefit - $1 billion losses = net loss in timber region of $0.3 billion). This example illustrates the need for regional climate scenarios and regional impact analysis.

Another disaggregation that would be interesting for future studies is to include demand for different kind of wood products. California produces some unique timber products and these might be less vulnerable to global trends. For example, will redwood products hold their price

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[5] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix XII

against increased production of other types of wood? Could the losses predicted above be offset by emphasizing replanting of redwood trees now?

3.9. Coastal Structures

The study of economic impact of level rise on coastal structures extends and improves the methodology used by Yohe et al. (1999), providing more spatial detail and a more nuanced treatment of the economic issues. Its findings illustrate a common yet important outcome of climate change impact analysis, namely, the non-linearity in response: a slow or moderate warming is likely to cause far less damage than a more rapid or severe warming. According to this study, the cost of protecting the coast against a 1-meter sea level rise is five times the cost of protecting against a 0.5-meter rise. Thus, actions to slow climate change can reduce the impacts considerably.

Another interesting finding is that along the developed areas of California's coastline, property values are likely to be sufficiently high that abandonment of developed land to seawater intrusion would not be an optimal response: protection against sea level rise would be economically justified at least from an overall economic efficiency perspective. The study focused on *developed* coastal areas, and for this reason it did not assess the potential impacts on wetlands and other "undeveloped" coastal areas. The authors clearly recognize that this is a limitation of their analysis. They call for forward-looking land-use planning around wetland areas to ensure that dry land just landward of vulnerable wetlands are protected from development in order to allow for the retreat of wetlands and the maintenance of at least part of their ecological and other values in the face of sea level rise. This is an important and useful suggestion because, currently, federal and state wetland protection extends only as far inland or upland as is periodically saturated by the current hydrologic regime (the criteria are signs of saturation in soil, wetland plants, or wetland species). Land immediately upland of the current habitat boundary is not protected from development, despite the potential significance of these lands for wetlands migration under future conditions of seal level rise.

The authors are careful to note other limitations of their analysis, including the need for more careful and detailed modeling of the expected inundation pattern in the Los Angeles area. They recognize that their assumption of perfect timing in the construction of protective structures is over-optimistic, and therefore understate the economic cost of sea level rise: if the protective structures are constructed some time before the precise moment at which they are required (which risk aversion would encourage) this would raise the discounted present value of sea level protection cost; whereas, if they are constructed some time after they become needed, in addition to the construction costs there also would be damage due to flooding in the interim.

The authors recognize two omissions which, if included, could also raise the estimated cost of sea level rise. One is the economic cost associated with the impact of sea level rise in the Sacramento River/San Joaquin River Delta, which could affect agricultural farmland and important elements of the state's developed water supply system as well as the aquatic ecosystem in the brackish part of the San Francisco Bay Estuary. Another item that could possibly be important is the effect of seal level change on the incidence of seawater intrusion into coastal aquifers, especially in vulnerable areas such as Southern California and the Monterey area.

The other omission noted is the economic cost of damage caused by storm surges as opposed to gradual sea level rise. These are likely to be exacerbated if ENSO intensification is coupled with

sea level rise. Storm surges are an important component of climate *variability* in addition to climate *change*. The former can be thought of as a shift in the variance while the latter is a shift in the mean. Both are likely to occur: climate change in California may come about through the increased frequency of storms and other extreme events; it is also logically possible to have a pure change in variability without a change in overall mean. Most of the existing economic literature ignores the potential cost of climate variability and focuses exclusively on climate change alone. Storms can cause economic loss in two ways: damage to coastal property (e.g., buildings damaged by flooding), and the disruption of economic activity located along the coast (e.g., due to lost income and or increased costs of production). Relative to the economic cost of protective structures, on which these authors focus, the cost of storm damages may weigh more in discounted present value calculations because these are likely to occur sooner—perhaps immediately—and they can occur multiple times at the same location. In addition to the damage that occurs when flooded buildings are rebuilt and then flooded again, there are the potential costs of beach nourishment which might occur several times at the same beach due to popular demand. As a result, the sea level rise costs reported here should be viewed as a significant underestimate.

3.10. Public Health

The study "Evaluation of California Health Data in Relation to El Niño Patterns"[6] was conceived as a limited and preliminary analysis of some of the potential impacts of climate change on public health. It focuses specifically on one particular aspect of the potential linkage between climate and health, namely the relation between variation in weather and variation in hospitalization rates for viral pneumonia, stroke, and cardiovascular diseases (acute myocardial infarction, angina and congestive heart failure). Other linkages are noted by the authors but not pursued, including the effects of extreme weather events on health, the effects of air pollution on health, and the effects of climate on water- and food-borne diseases and on vector- and rodent-borne diseases.

Given the specific focus on weather-related variation in hospitalization rates for the three types of illness, the authors conducted their investigation by fitting a Poisson model to daily hospitalization data from January 1983 to June 1998 separately for each of three pairs of urban counties: Sacramento / Yolo counties, San Francisco / San Mateo counties, and Los Angeles / Orange counties. The results vary quite a bit between regions. For example, in the San Francisco and Los Angeles areas, hospitalizations increased significantly with a decrease in minimum temperature while, in the Sacramento area, they increased significantly with a decrease in the maximum temperature difference (the difference between maximum and minimum daily temperature). El Niño events were significantly associated with increased hospitalization for cardiovascular disease for both men and women in the San Francisco area; in the Sacramento area, these events were associated with increased cardiovascular hospitalization for women; in Los Angeles, they were not significantly associated with increased hospitalization for either sex. It is not clear how to interpret the variation in these and other

[6] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix XIV

results, and they should probably be considered as exploratory in nature. The authors indeed emphasize that their analysis is intended to generate, rather than test, hypotheses.

The analysis here differs from some of the other literature on the effects of weather on health in at least three ways. First, the dependent variables in this study are daily rates of hospitalizations; whereas, some of the other studies in the literature have used daily mortality rates. Second, to measure the effects of weather, this study uses a suite of direct climate variables. Studies by Kalkstein and various collaborators have used a synoptic categorization of weather situations as the measure of climate. Third, the studies by Kalkstein identify thresholds effects: temperature affects mortality when it falls below a threshold of extreme cold or rises above a threshold of extreme heat. Typically, the thresholds are estimated separately for different cities, and the regional differences in thresholds reflect differences in the nature and degree of people's adaptation to their local climate. This study estimates a model in which the mean of the Poisson model, λ, is assumed to be monotone in the climate variables, $\lambda = e^{x\beta}$. An alternative would be to make λ a nonlinear (e.g., quadratic or cubic) function of climate, as was done by Shumway, Azari, and Pawitan (1988) in a time-series modeling analysis for Los Angeles County.

Another issue to be considered in any future work is whether the Poisson model might be too limiting, because, while it allows covariates to affect the variance, it somewhat constrains their influence on the variance because it makes the variance proportional to the mean. A more general model of the variance could be considered. Moreover, the results obtained here could be influenced by the averaging of mortality rates and weather variables over four-day periods, which might perhaps attenuate the relationship between weather and mortality. If it is necessary to reduce the number of observations to accommodate computational restrictions, one might estimate separate regressions for, say, winter versus summer days. The time aggregation might be an unnecessary complication; at the least, it complicates the search for an optimal lag structure.

Overall, this study is a useful first start in what needs to be a more sustained and systematic effort to explore the potential of climate change and variability to affect human health in California. In addition to impacts noted by the authors, including the health effects of extreme weather events, the health effects of air pollution, and the effects of climate on water- and food-borne diseases and on vector- and rodent-borne diseases, the state might want to consider unexpected impacts. For example, if the HADCM2 prediction of 50% more rainfall occurs, this would greatly increase road dangers and power outages. The resulting increase in traffic fatalities might be as large a public health impact as the more direct climate change impacts on health. Clearly, this is a topic that could benefit from more study and response by the state, and in particular by the state agencies responsible for public health and safety. One can envision the increased need for multi-agency cooperation regarding regulatory issues, emergency response planning, and surveillance, detection and attribution as alternative forms of climate change adaptation policy.

3.11. Baseline Projections of California's Urban Footprint

This is a fascinating study to forecast where Californians will be located in the future.[7] It can provide important baseline information for several of the climate change impact studies where

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[7] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and*

spatial location and land use patterns play a key role, including the studies of future urban and agricultural water demands, future energy demand, and future impacts on terrestrial ecosystems, vegetation, prospects for adaptation, and fire regimes.

The foundation for the forecasts is a set of statistical models tracking the spatial patterns of urban development in Southern California, Northern California, the Sacramento region and the southern San Joaquin Valley between 1988 and 1998. The models are used together with assumptions about the future share of infill versus greenfield development and future population densities in new growth areas densities. These factors are combined with Department of Finance projections of county-level population growth to generate forecasts of the future location of urban growth in California. The authors are careful to note the limitations in these forecasts, including reliance on the key assumption that the same factors that shaped land development patterns during the period 1988–1998 will continue to do so in the future, and in the same way. Although some version of this assumption is unavoidable in a forecasting exercise, we believe it would be desirable in future work to attempt to develop some form of confidence interval or uncertainty bound to supplement point estimate forecasts of urban growth.

3.12. Energy Expenditures

The study of energy expenditure impacts[8] builds on and extends the methodology developed by Morrison and Mendelsohn (1999). It employs a two-part model of energy expenditure; the first part models the probability that an individual structure has central cooling, and the second part models the total expenditure on energy by the structure's owner. In the second part, two versions of the energy expenditure equation are estimated, one intended to correspond to short-run demand and the other to long-run demand. The entire two-part model is estimated separately for residences and for commercial buildings using data on a national sample of individual households and individual businesses from the U.S. Department of Energy's 1990 Household Energy Consumption and Expenditures survey and its 1989 Commercial Buildings Energy Consumption survey. The fitted models are then used to predict the impacts of various climate change scenarios for California measured in terms of increased expenditure on energy by households and commercial businesses in 2020, 2060, or 2100.

Although the study pursues an important objective, we are concerned that the scope of what it can actually accomplish is limited because of some problems with the data and the analysis.

The dependent variable for the demand models is the household's (or the firm's) total expenditure on all forms and all end uses of energy during the year covered by the survey. As the author notes, this differs from other studies in the literature that have focused on the demand for particular forms of energy (e.g., electricity or natural gas) or particular end uses. In effect, this study treats energy as a Hicksian composite commodity. Technically, the condition required for Hicksian commodity aggregation to hold is that the prices of the different

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the Economy. August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix III

[8] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix XI

component commodities should vary in fixed proportion across the sample. It is unlikely that this holds in the case of aggregate energy expenditures; the ratio of electricity to natural gas prices, for example, varies quite markedly across states and regions.

If the Hicksian aggregation condition does not hold, total expenditure on energy must then be viewed as simply the empirical aggregate of several *separate* demand functions for individual fuels and/or end uses. This situation can lead to instability in the coefficients of the combined aggregate equation. For example, the demand for energy for heating may fall with an increase in temperature in the spring, while the demand for energy for cooling rises with springtime temperature. The combination of the two demand functions could rise or fall with springtime temperature, depending upon the specific shares of heating versus cooling in the aggregate household demand for energy. These shares are themselves endogenous: shifts in the various explanatory variables can lead to shifts in the relative proportions of heating versus cooling and, hence, to shifts in the aggregate demand elasticity. If cooling is more sensitive to temperature in May than space heating, say, an increase in May temperature will increase the share of cooling in total energy demand and, hence, make overall energy demand more responsive to May temperature. In the absence of Hicksian aggregation, there may not be a stable aggregate demand function. In this regard, it would be better if the data permitted the estimation of separate demand functions for heating and cooling. Failing this, it could be better to estimate separate demand functions for electricity and/or natural gas, since these may be used differentially with heating versus cooling; as noted earlier this has been the usual approach in the existing literature.

The study is in the position of using cross-section data from a single year to predict the dynamic response to changes in energy prices, income, and housing/building stocks in California at various times in the future. Given the available data, this research strategy is unavoidable, but it is still hardly desirable. We feel that the development of an econometric model based on multiyear data is a high priority for future work on energy impacts. We note that the Energy Information Administration (EIA) now has data from a 1997 residential energy consumption survey which could now be combined with the data from the 1990 survey for a dynamic analysis. It also would be useful to consider other potential sources of data. In some cases, an energy utility company has itself conducted multiyear surveys of energy use and appliance ownership among its customers—for example, Hydro-Quebec (Bernard, Bolduc, and Belanger 1996)—and in some other countries the national household expenditure survey provides a rich source of data on residential energy use and appliance ownership over a long period of time. Examples include the UK (Baker and Blundell 1991; Baker, Blundell, and Mickelwright 1989) and Norway (Halvorsen and Larsen 2001). Unfortunately, the U.S. Consumer Expenditure Survey is not as useful or reliable a source of data as the equivalent surveys in the UK and Norway. In this regard, the Canadian Household Expenditure Survey appears to be superior to the U.S. version and more akin to the UK or Norwegian versions. Given the geographical proximity and potential similarity of residential structures and lifestyles between at least some areas in the two countries, one may want to consider using the Canadian data to develop a dynamic model of residential energy demand that could be applied for modeling some U.S. climate change impacts.

Because these impacts on energy use will occur 20, 60, or 100 years hence, it is impossible to predict them with much accuracy, regardless of the data and the form of the energy demand model, because so many factors could intervene and change the demand for energy. This uncertainty includes such factors such as de/regulation of the energy industry or changes in its

structure and governance, changes in the technology or availability of inputs for electricity generation, changes in energy conservation technologies, and the possible introduction of carbon taxes. Events like this, which are outside the model and could cause structural change to the model entail a substantial level of uncertainty associated with forecasts of future energy impacts that needs to be acknowledged.

The weather data in the original EIA survey measured weather conditions in the year of the survey. Instead, this study replaces these variables with measures of long-run climate for the county in which the household / firm is located, which could be a mixed blessing. For the purpose of explaining whether or not a structure has central cooling, long-run weather conditions *prior to the date of construction* are likely to be a dominant factor. Our impression is that retrofitting to install central cooling (as opposed to air conditioners that fit in windows) is relatively rare, so that weather conditions *after* construction are unlikely to have much influence on whether or not there is central cooling. But, we would expect current weather conditions in any given year to have a strong influence on energy expenditures because they affect the intensity with which household or firm operates its heating and cooling equipment during the year. Therefore, it seems less appropriate to employ the long-run climate variables in the energy expenditures equations. Furthermore, the long-run climate variables are countywide spatial averages which, in some cases, may be an undesirably coarse level of aggregation. To the extent that weather conditions in counties are spatially heterogeneous (one thinks of Contra Costa County, where the temperature in Richmond is often 10–20 degrees cooler than the temperature in Walnut Creek), the countywide averaging induces a form of measurement error which is likely to bias the estimate of the regression coefficients towards zero.[9]

Furthermore, instead of using the specification of weather that is more conventional in the energy demand literature, which is framed in terms of cooling and heating days, this study uses temperature and precipitation in January and July. While this focus has a clear advantage in terms of relating this energy research to variables that are relatively accessible from climate models, it is possible that this comes at the cost of weakening the meaningfulness of the energy model itself. It is not entirely obvious to us why January temperature should affect the household's decision to install central cooling, or why January precipitation should affect the firm's decision to install central cooling. To the extent that average temperature and precipitation for the various months are correlated over the long-run, the regression results could be an artifact of the multi-collinearity; the January climate variables could be picking up the effect of some *other* climate variables that happen to be correlated with them. To the extent that multi-collinearity is a factor in the regression results, it could diminish their reliability for the type of forecasts being made here in the event that the pattern of correlation among monthly temperature and precipitation changes with future climate change.

In addition, the economic analysis departs from the conventional approach in the energy demand literature with regard to the calculation of welfare impacts and the treatment of long- versus short-run impacts.

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[9] In addition, the failure to correct for group effects when combining county-wide regressors together with an individual-level dependent variable can make the ordinary least squares standard errors used in this study significantly downward biased (Moulton 1986, 1987).

For welfare calculations, the study uses the fitted model to predict change in total energy expenditures and takes this as the monetary measure of the household's welfare loss. By contrast, most studies in the literature estimate some form of demand function that is associated with a known direct or indirect utility function and they use this utility function to calculate the Hicksian compensating or equivalent variation for the change in question. It generally is not true that changes in expenditure provide a good measure of the monetary value of an individual's change in welfare as represented by the Hicksian variations. For example, if price falls, the individual's welfare unambiguously improves, but if demand is elastic, her expenditure increases; in that case, the change in expenditure is in the opposite direction to the change in welfare.

The study justifies its use of the change in expenditures to measure a change in welfare by appealing to empirical evidence that households maintain their interior temperature at a level that is almost identical across the country. We are not convinced that the empirical assertion is always correct; casual empiricism suggests that the indoor temperature in homes in Berkeley which lack air conditioning is often higher in the summer than the indoor temperature in homes in Walnut Creek which possess air conditioning. Even if the assertion were true, however, by itself it does not automatically imply that the change in expenditures exactly measures the compensating or equivalent variation associated with a change in climate—some other assumption is needed. First, the claim rests on a story about the demand for energy for space conditioning, not other forms of energy. Second, it implies that the utility function has a specific mathematical form with respect to space conditioning as a commodity which entails, among other things, that the demand for space condition is independent of prices and income; as far as we know, the empirical evidence does not support this. Third, it implies that climate variables do not enter the utility function in any way except as an input to the household production function for space conditioning—in other words, that the household cares nothing about the weather except insofar as it has the potential to affect the indoor temperature. Again, we are not sure that this is true.

Starting with Fisher and Kaysen (1962), the energy demand literature has been sensitive to the distinction between short- versus long-run price elasticities of demand based on the fact that much household (and industrial) energy use is tied up with the ownership of particular energy-using capital assets (e.g., household appliances). Because these assets are somewhat long-lived, the expectation is that that they are unlikely to be replaced whenever energy prices change—they may subsequently be replaced sooner than would have occurred had energy prices not changed, but they are unlikely to be replaced immediately. Hence, the short-run response to a price change reflects just the change in the rate of utilization of the given stock of appliances, while the long-run response reflects both that and also the subsequent modification in the stock of appliances. In many cases, the evidence suggests that the response associated with the change in capital stock is substantially larger than that associated with the change in the rate of utilization

While the present study makes a point of accounting for the distinction between long- versus short-run demand responses, it does so in a manner that is non-standard in the literature. In this study, the way that the distinction between short- and long-run responses is implemented is to employ two different sets of regressors in the energy expenditure equation. What this study calls the "short-run demand model" uses the full vector of household (or firm) variables, including building characteristics such as whether the structure has central air conditioning, whether there are window or wall air conditioners, and whether there is electric wall heating—

in addition to economic variables such as electricity price, natural gas price, household income, demographic variables such as family size and ethnicity, and the full suite of climate variables noted above. What this study calls the "long-run demand model" omits the building characteristics but continues to include the economic variables, the demographic variables, and the climate variables. The rationale for the omission of the building characteristics variables is that they are inherently endogenous and, in the long run, they will change in response to changes in the climate and / or economic variables.

By contrast, the conventional approach in the energy demand literature involves the estimation of just one function for energy usage with the full set of regressors, including building characteristics, which is viewed as a conditional, or short-run, demand function for energy. To obtain the short-run price elasticity of demand, say, the researcher differentiates the short-run demand function with respect to price, holding all other variables constant (including the building characteristics). To obtain the long-run price elasticity of demand the researcher obtains a long-run demand function for building characteristics either by estimating a separate set of demand functions for the presence of individual characteristics (like this study's logic model for the presence of central cooling) or by setting up and solving a long-run utility maximization for the purchase of building characteristics based on solving a budget-constrained maximization of the conditional utility function underlying the estimated short-run demand function for energy usage. Then, the long-run price elasticity of demand is obtained by combining the short-run elasticity with an elasticity based on differentiation of the long-run demand for building characteristics. Thus, while the approach used here for estimating short-run elasticities of demand is the same as that used in the existing literature, the approach for estimating long-run elasticities of demand is different.

We find the approach used here for estimating long-run elasticities to be problematic for several reasons. For one thing, the approach is not applied consistently. In the residential model, for example, while variables such as home area and the presence of a basement are treated as endogenous (along with whether the structure has central air conditioning, whether there are window or wall air conditioners, and whether there is electric wall heating), some *other* variables (including the number of floors, the number of rooms, whether the tenant controls heat, whether there is a color TV, whether there is a computer, and whether there are appliances) are treated as exogenous and are not dropped from the study's long-run demand equation. The difference in treatment seems odd. Beyond this, however, the approach used is logically inconsistent. If one believes that certain variables on the right-hand side of the energy demand equation are endogenous and are affected by the disturbance term in the model (i.e., the disturbance term is "transmitted" to the decision equation for these endogenous variables), these variables will not be independent of the error term in the energy demand equation. In that case, including these variables damages the estimation of the energy demand equation and renders coefficients estimated by ordinary least squares (OLS) asymptotically biased (inconsistent); in principle, the bias affects *all* the coefficients, not just those of the endogenous variables. Therefore, if building characteristics truly are endogenous within the time frame comprehended by the energy demand equation, the so-called short-run demand function is not estimated reliably. Rather than calling one of the study's two energy demand equations "short-run" and the other "long-run," it would be more accurate to refer to one as a "structural equation" and the other as a "reduced form equation."

In fact, however, the bulk of the energy demand literature assumes that the disturbance term in the model is *not* transmitted to the building characteristic variables. These are viewed as

predetermined on an annual basis and contemporaneously uncorrelated with the error term in the energy demand equation. In that case: (1) an energy demand equation including these variables is validly estimated by OLS, (2) the derivatives of this equation with respect to such factors as price, income, and others lead to the short-run demand elasticities, and (3) the long-run elasticities are obtained by estimating an equation for the determination of each building characteristic (the long-run demand equations for these variables). This is how the existing literature on energy demand proceeds, and it strikes us as more appropriate than the approach adopted here.

3.13. Agricultural Yield and Water Use

The study of the effects of climate change on yields and water use of major California crops[10] is designed to provide input to the Statewide Water and Agricultural Production (SWAP) model and to CALVIN, the statewide optimization model of water supply and allocation. The approach employed in this study is to estimate regression equations of yield and water use on various climate variables using annual data from panels of California counties. This is similar to the approach adopted by Segerson and Dixon (1999) for a group of Midwest states, except that Segerson and Dixon used as their dependent variables crop yields and farm profits but not crop water use.

The source of the data for the crop water use regressions is the quinquennial U.S. Geological Survey (USGS) report on national water use, specifically the section on irrigation water use by state and county for 1985 and 1995. However, from our understanding of the existing data on agricultural water use in California we are concerned that this data may not be sufficiently reliable to serve the purpose intended. The USGS National Water-Use Program relies on local sources for its data as much as possible; however, there are some significant questions about the reliability of the existing California data on agricultural water use. In California, only surface water deliveries of irrigation water are monitored; groundwater pumping for irrigation is not monitored or measured in any way. The Department of Water Resources uses satellite observation to measure crop acreages by county, and it estimates irrigation water use by applying specific assumed crop-water use coefficients to the crop acreages. Groundwater use is then estimated by subtracting the measured surface water delivery from the assumed total water use. The crop-water use coefficients employed for estimating total water use are based on expert judgment, not on direct observation. Our concern is with the lack of direct measurement. If the crop water use coefficients overstate irrigation efficiency they will understate both total water use and also groundwater pumping. In the past, we have seen several pieces of evidence which suggest to us that the existing crop-water use coefficients are likely to be overstating irrigation efficiency to some degree. Absent direct measurement of total water applied for irrigation in California, the official data must be treated with great caution. Furthermore, to the extent that some counties rely on (unmeasured) groundwater pumping more than others, the margin of error in the existing estimate of total water use is likely to vary from county to county.

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[10] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix IX

By contrast, the data used for the yield regressions are less problematic. These are annual data on crop acreage and crop yield covering the years 1972 through 2000 and they come from National Agricultural Statistics Service, which in turn relies on annual reports from the County Agricultural Commissioners in California. While the data undoubtedly contain some measurement error, this is likely to be within a normal range and the data should be considered reasonably reliable.

Nevertheless, there are some potential statistical issues with the yield equations, some of which are fully acknowledged in the study. Two issues that are acknowledged are heteroscedasticity and multicollinearity. The yield data are averages over all land growing the given crop in the county. To the extent that counties differ in size and the amount of land allocated to the given crop varies from county to county, the yields are averages over different numbers of acres from county to county; as averages, they will have standard errors that vary inversely with the square root of the given cropland acreage in the county. This generates heteroscedasticity in the disturbance terms of the yield regression equation. In the presence of heteroscedasticity, OLS coefficient estimates are still unbiased and consistent, but the conventional formula for the covariance matrix of the OLS estimator is incorrect. Faced with a similar problem, Segerson and Dixon (1999) employed White's consistent estimator of the OLS covariance matrix, but that is not done here. The reason could be the multicollinearity among the regressors, which are mainly 24 climate variables: average maximum daily temperature in the county in March, April, May, June, July, and August (the growing season); monthly precipitation in the county in March, April, May, June, July, and August; and the squares of each of these 12 variables.[11] These variables—especially the squared terms—induce a substantial degree of multicollinearity. The significance of multicollinearity in OLS regression is that it is not possible to separate out the specific effect of the individual regressors with any accuracy: individual regression coefficients are likely to be highly unstable (they may even have the "wrong" sign), and they may have very high individual standard errors even though they are *jointly* highly significant.

Given these problems with the individual coefficients and their standard errors, the authors of this study may have decided that using White's corrected covariance matrix would be pointless. Following Segerson and Dixon (1999), they argue that the OLS coefficients are still meaningful when used for climate change simulation because this involves a scenario where *all* temperature variables and *all* precipitation variables are changed by some common amounts: given the common factors of proportionality, the unreliability of individual coefficients should not matter. We accept this argument, but only up to a point. The larger issue is that climate change scenarios involving a common proportional shift in temperature or precipitation across all the months of the year are likely to be far too crude for use in future climate change analysis for California and, then, the reliability of the individual coefficients *will* matter. It will then be necessary to look for an alternative estimation strategy that deals with the multicollinearity more successfully. One possible approach is to employ fewer climate variables that, individually, are more meaningful— something analogous to the use of degree days in the electricity demand literature.

There are two other possible econometric issues that could have been considered. First, in using simple OLS estimation, the study ignores the fact that the data have a panel structure—they

[11] In addition, there are three other regressors: a time trend variable and two land quality variables—the percentages of high- and medium-quality cropland in the county.

involve repeated observations on the same counties over a period of time. This has two important statistical implications. First, the errors terms in the regression equation may have nested (hierarchical) structure in which the overall error term associated with t^{th} observation on the ith county, ε_{it}, is composed of two components: one specific to the county, υ_i, and another that is truly random across counties and years, ω_{it}.[12] The county-specific component can be thought of a representing unobserved characteristics and attributes of the county which affect crop yield but are not included among the regressors. Under this formulation, known as the random effects model, the regression errors terms are heteroscedastic. By itself, this does not threaten the consistency of the OLS coefficient estimates, including those of the climate variables, but it renders them inefficient. The second implication, which has more serious consequences, is that there may be some correlation between the climate variables in a county and the county effect, ν_i. In that case, the correlation between ν_i and the climate variables would make the OLS coefficients no longer consistent. An alternative to the random effects formulation is a fixed effects model in which the regression equation has a separate intercept for each county. Application of OLS to the fixed effects model generates a different, fixed effects, estimator of the climate coefficients which is an alternative to both the random effects GLS estimator and the simple OLS estimator. It can be shown that the fixed effect estimator has a somewhat looser requirement for consistency than the random effect estimator, namely that the weather variables be uncorrelated not with ω_{it} but instead with deviations of ω_{it} from their average over the overall time period. A third estimator is the first difference estimator in which one takes differences in yield between successive pairs of yields and regresses this on the corresponding differences in the right-hand side variables. Under the assumption that the ω_{it} are serially uncorrelated, the fixed effects estimator is more efficient than the first difference estimator, but this is reversed when the ω_{it} follow a random walk. These three estimators—random effects, fixed effects, and first differences—might produce different substantive implications for the effects of climate on crop yield, and they merit consideration as alternatives to the simple OLS estimator.

The other issue that is not addressed (and cannot be addressed with the currently available data) is the bias that might be introduced by the use of county-wide rather than field-level data. One aspect of this issue is measurement error arising from the attempt to represent diverse weather conditions within a county by a simple county-wide average; this could generate the county effects, ν_i, mentioned above. Another aspect is that the possibility of a form of adaptation-induced selection bias arising from the fact that the crop is not necessarily growing in the same fields every year. Suppose, hypothetically, that farmers plant different crops in a given field when weather conditions change; in a dry year, for example, the farmers plants a different crop than in a wet year. In that case, the county-wide average yields are being averaged over different sets of counties from year to year. If there were field-level data, one could test for this type of selection behavior and control for it by modeling it explicitly.

We end with two short points. First, we note that the model output from the two warm wet scenarios (HadCM2 and T5P30) gave qualitatively different results.[13] The reason for the

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[12] There could be also another component that varies purely with time, θ_t.

[13] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix IX

differences is that the seasonal and regional patterns in the GCM, which are missing from the incremental scenarios, drive some of the results. As a result, it should not be assumed that the GCM scenarios bracket the range of likely responses or that the incremental climate scenarios form a continuum between the two GCMs. The second point concerns the regression model of plant yield and water use. The model was run with different combinations of elevated CO_2, climate change, and technological improvement (0.25%/y for 100 y). It was not run with a full factorial of these effects, however. Keeping track of which models were run with which inputs can be difficult in reading this report and interpreting the summary table, which demonstrates the need for sector scenarios, as described above.

3.14. Climate Warming and Future California Water Management

The studies described here[14] combine a suite of climate change scenarios, simulations of changes in streamflow, forecasts of climate-induced changes in crop yields and crop-water requirements and economic models of agricultural and urban water use, together with an optimizing model of statewide water allocation to assess the impact of climate change on users of water in California. This is a complex an ambitious analysis. Because it is so comprehensive and involves so many components, it inevitably may be no stronger than its weakest link.

On the economic side, key inputs to the model are the marginal valuation functions for urban and agricultural users at various locations around the state. We have some concerns about the particular approaches used by the CALVIN model to represent these values. For urban water use, we believe it is important to recognize the distinction between *long*- versus *short*-run demand functions. The distinction is of some consequence because short-run demand for urban water is likely to be considerably more inelastic than the long-run demand. We believe that the short- and long-run demand functions are applicable to *two different* types of water shortage scenarios, both of which are likely to be generated by climate change at some point in the future. One is a sudden drought emergency, for example, when a city announces in March that customers will have to cut back water use by 15% starting July 1. In this case, the relevant demand function for predicting price responsiveness and measuring the loss of consumer's surplus is the short-run demand function, not the long-run demand function. Alternatively, in the case of a shortage that builds up slowly over a long period time, perhaps due to a secular increase in urban population combined with a long-run reduction in the available surface water supply, the long-run demand function is likely to the appropriate one for assessing price responsiveness and for measuring the loss of consumer's surplus. Both types of shortage could occur as the consequence of long-run climate change in California. However, as we understand it, CALVIN employs a single demand function in each zone, which is long- rather than short-run in nature. This would understate the adverse impact of a sudden drought emergency on urban water users.

In the case of agricultural water use, the demand functions in the California Agricultural Resources Model (CARM) are not based on direct observation of water use by California farmers; they are based on assumed crop-water use coefficients combined with a prediction of cropping patterns that is generated by an optimization model. The crop optimization itself

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[14] See *Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy.* August 2003. California Energy Commission, PIER Environmental Area. P500-03-058CF. Appendix VII

involves several features that are questionable, including what may be an overly broad choice set and a narrow focus on variable costs of production to the exclusion of fixed costs.

The statewide water allocation embedded in CALVIN involves several assumptions that are unrealistic, including the assumption that, from one month to another, water can be reallocated from any agricultural or urban user in California to any other, and from any one part of the state to any other, based simply on the criterion of maximizing profit plus consumer's surplus, regardless of institutions, uncertainty or disagreement about water rights, or anything else. Moreover, the month-to-month optimization is conducted with perfect foresight over a period of 72 years.

The researchers readily concede that many of the assumptions are over-simplified and unrealistic. The question is whether these simplifications impart a systematic bias to the conclusions derived from the model. We believe this may be the case. The simplifying assumptions generally tend in the same direction, namely to overstate the ease of substitution among inputs, among outputs, among uses of water, and among users in different regions. To the extent that an optimization model exaggerates substitution possibilities and understates adjustment costs or other impediments to substitution, it is likely to understate the economic cost of shocks to the economic system—such as climate change—that disturb an existing equilibrium.

One further comment concerns a limitation in the underlying hydrologic data that drive CALVIN. These are a series of historical monthly streamflows covering a period of 72 years, modified to adjust for current (1990) development conditions in California. The data were developed by the California Department of Water Resources; they show what the streamflow in a given reach of river would have been in, say, March or April or May 1927 if the modern population of California had been living in the region and diverting water instead of the actual population that lived there in 1927. In order to explain the limitation inherent in these data, it is necessary to make a distinction between *variability* and *uncertainty*. The data certainly capture the variability in streamflow in California—in the spring of 1927, there was a lot of rain and a large streamflow in this river, while in the spring of 1928 there was a drought and little streamflow in the river. But, the actual streamflow in any month or any year represents the realization of a random variable. *Ex ante*, before the realization, one has actual uncertainty: ahead of time, one does not know what the streamflow will be. We believe that the existing hydrologic data do not adequately represent the ex ante uncertainty facing water users in California. We also believe that this uncertainty may have important economic consequences for the water use and allocation in California. We speculate that it is the ex ante probability of obtaining water during the future—especially during the summer—which has the most powerful influence on water users' decisions. This applies to agricultural uses (by irrigation districts), urban uses (by regional and municipal water agencies), and environmental uses (in-stream flows). Furthermore, we speculate that these decisions may typically embody a significant degree of risk aversion; hence, it is not just the mean of the ex ante probability distribution of obtaining water that influences water users but also other features such as the tail probabilities. If these surmises are correct, they could have some important implications for modeling the economic effect of climate change on water use in California since one effect of climate change may be increased uncertainty regarding streamflow and surface water supply. This uncertainty could impose economic costs beyond those that are considered in the current study.

4.0 Conclusions and Recommendations

In recognition of the nascent state of climate impact science, we suggest that the study's findings be viewed not as specific predictions, but as a sensitivity analysis that considers a range of potential outcomes.

As we noted at the outset, this study constitutes a significant step forward in the analysis of regional climate change impacts in the United States. We have discussed both strengths and weaknesses of the analysis and, in several instances, tried to place the work in the context of larger developments in science and policy analysis that bear both on interpretation of the results and on future potential extensions. We hope and anticipate that this study will provide a benchmark for future efforts, in California and elsewhere, to anticipate and plan for regional impacts of climate change.

In conclusion, we here summarize a number of our key recommendations. Before proceeding to topic-specific suggestions, it is appropriate to highlight the crosscutting need for substantial new efforts to incorporate uncertainty into this type of analysis. This need is reflected, for example, in our recommendations for including stochastic information in climate projections, for applying adaptive environmental decision-making principles, and for addressing the deep uncertainty intrinsic in climate-related socioeconomic projections over decadal or centennial time scales. In a larger context, it is well recognized that incorporation of uncertainty (and resulting policy-relevant risks) into the global-scale "integrated assessment" of climate change is a high priority that, to date, has been underemphasized by both the scientific and the economic-and-policy-modeling communities. In our view, the present study demonstrates that this need is a priority present in regional-scale analysis as well.

Following is a summary of other key recommendations:

- Create a set of official California climate scenarios that incorporate regional specificity, stochastic information (such as temperature and precipitation variability), and additional relevant variables.
- Develop an integration and synthesis framework for analyzing impact interactions among sectors and for formulating coordinated, adaptive policy responses.
- Support or, as appropriate, exploit developments in dynamic vegetation modeling to reduce uncertainties regarding transient responses (among other factors), and to improve the representations of a range of bio-physical and relevant climatic effects.
- Include sub-regional specific detail and climatic variability effects in the analysis of coastal impacts.
- Extend public health impact analysis by incorporating more general and flexible representations of variance in incidence modeling and by including a broader range of potential impacts drivers.
- Explicitly incorporate uncertainty into urban growth projections.
- For the modeling of climate change impacts on energy demand:

1. Obtain the data resources needed to:

   a) Disaggregate the energy composite used in this study,

b) Long-run trends from time series rather than cross-sectional observations, and corporate explicit models of heating-and-cooling degree days in order to estimate climate change impacts.

2. Develop and estimate new econometric models drawing on these data and reanalyze welfare effects, including improved treatment of long versus short-run elasticities

- Experiment with alternative estimators besides ordinary least square in econometric models of climate change impacts on crop yield, and seek to obtain more disaggregated data.
- Develop and apply non-optimizing models of climate change impacts on California water supply and demand, complementary to the optimizing model used in this study, in order to more accurately gauge substitution possibilities and adjustment frictions.

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