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FINAL PROJECT REPORT

CLIMATE CHANGE IMPACTS ON GENERATION OF WIND, SOLAR, AND HYDROPOWER IN CALIFORNIA

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PREFACE

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Climate Change Impacts on Generation of Wind, Solar, and Hydropower in California is the final report for the Climate Change Impacts on Generation of Wind, Solar, and Hydropower in California project (Contract Number 500-06-044) conducted by Lawrence Livermore National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

This study assessed the potential impacts of global climate change on the ability to generate electricity in California from weather-dependent renewable resources such as wind, solar, and hydropower. Researchers used a sequence of numerical models that simulated climate, surface hydrology, wind power generation, and high-elevation hydropower generation. The models predicted small to modest decreases in potential electricity generation from each of these resources. Hydropower showed the greatest decrease of the three. These results, however, were highly dependent on the choice of climate models and based on a decrease in annual precipitation in the study region projected by the climate models researchers used. These models were not unique in this regard, but other models projected increases in precipitation and would give more optimistic results for hydropower generation. The projected decrease in wind power may also be specific to the models researchers used but was quite modest. The projected decrease in available sunlight for solar power generation was statistically significant and robust across models, but was also very small. Researchers recommended additional assessments using other models, particularly for wind and hydropower. Study findings will benefit California ratepayers by enabling upfront consideration of future effects of climate change on renewable resource potential.

Keywords: California, climate change, wind power, solar power, hydropower, hydroelectricity, renewable

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EXECUTIVE SUMMARY

Introduction

Climate change is a key motivation for increasing the production of electricity from renewable resources. Among these resources are renewable forms of energy including wind, solar, and hydropower. These resources are weather-dependent, so it is possible in principle that climate change could affect the ability to produce electricity from them.

California has sizable hydropower resources and small but growing wind and solar resources. The state has adopted aggressive Renewables Portfolio Standard (RPS) targets aimed at reducing its dependence on fossil fuels and increasing the generation of electricity using renewable resources. It is important to understand how climate change—which is a primary reason for the existence of RPS targets—might affect California's ability to meet its RPS targets.

Project Purpose

This study assesses the impacts the modeled scenario for future climate on electricity generation from three renewable resources (wind, solar, and hydro) in California, first in isolation, and then considered in total.

Project Results

In this report, researchers estimate the effects of increased atmospheric greenhouse gases (climate change) on potential power generation in California from these weather-dependent renewable resources using a linked sequence of numerical models. The approach bases all assessments on the results of one global climate model. This provides a completely self-consistent approach but, for the most part, sacrifices the ability to assess the robustness of the findings.

Understanding the potential impacts of climate change on California's ability to generate electricity from weather-dependent renewable resources is an important consideration in planning how to meet those goals. This study definitively addresses some aspects of this problem (for example, potential impacts on solar power generation). For other aspects, it identifies topics requiring additional investigation.

Results show that downwelling solar fluxes at ground level—which determine the potential for solar power generation—are predicted to decrease very slightly in the summer season, resulting in a corresponding reduction in solar power production. It is, however, unlikely that climate change would significantly impact the ability to generate electricity from the sun in California. A possible exception is in coastal regions where future changes in fog may be significant and cannot be predicted with confidence. Regions subject to fog, however, are not considered good candidates for large-scale solar power production.

Results for wind-generated electricity indicate a small decrease in potential power production in Tehachipi in some seasons, especially fall. This result in particular should be considered preliminary, as predicted wind speeds can be sensitive to specifics of the model such as treatment of soil moisture and assumptions about land-use change. In addition, other regions such as Altamont might have different trends and should be studied.

The study findings for hydroelectric power generation show significant reductions that are a consequence of the large predicted reduction in annual mean precipitation in the global climate models used. Reduced precipitation and resulting reductions in runoff result in reduced hydropower generation in all months and elevation bands. These results indicate that a future that is both drier and warmer would have important impacts on the ability to generate electricity from hydropower. This finding is hydrologic model-dependent; there is not a strong consensus among the CMIP3 global climate models as to whether California will see an increase or decrease in annual-mean precipitation—although more than half of the models predict a decrease (Cayan et al. 2006).

More research is necessary to investigate the effects of potential climate change impacts on the ability to generate electricity from wind and hydropower. Wind speeds in a future climate will depend on the complex interaction of climate factors such as near-coastal upwelling, offshore winds, fog, and soil moisture. The future behavior of these factors and the interplay among them is uncertain, but the prospects to reduce those uncertainties are optimistic.

Project Benefits

This project provides a better understanding of potential climate change related changes to the solar, wind and hydropower resources in California that will help guide planners seeking to install new wind, solar and hydropower generation capacity in the state. Upfront planning for climate change contingencies will help mitigate risks involved in establishing greater reliance on renewable generation, thereby benefiting California ratepayers.

CHAPTER 1: Introduction

1.1 Background and Overview

Established in 2002 under Senate Bill 1078, California's Renewables Portfolio standard was accelerated in 2006 under Senate Bill 107 by requiring that 20 percent of electricity retail sales be served by renewable energy resources by 2010. Subsequent recommendations in California energy policy reports advocated a goal of 33 percent by 2020, and in 2008, the governor signed Executive Order S-14-08 requiring that "[a]ll retail sellers of electricity shall serve 33 percent of their load with renewable energy by 2020." The following year, Executive Order S-21-09 directed the California Air Resources Board, under its Assembly Bill 32 authority, to enact regulations to achieve the goal of 33 percent renewables by 2020.

Increased production of electricity from renewables, although desirable from environmental and other viewpoints, may create difficulties in consistently meeting demand for electricity and may complicate the job of operating the state's transmission system. This would be true of any major change in electrical supply portfolio but is especially so when the proportion of weather-dependent renewables—which are subject to uncontrolled fluctuations—is increased.

In addition, climate change may affect the ability to generate needed amounts of electricity from weather-dependent renewable resources and thus may compromise California's ability to meet renewable targets. For example, it is well documented that climate change is affecting the seasonal timing of river flows such that less hydropower is generated during months of peak demand and maximum electricity value. Generating solar and wind power may also be impacted by long-term changes in climate.

1.2 Project Objectives

This project makes a unified assessment of potential climate change impacts on three important, weather-dependent renewable resources: wind, solar, and hydro. The researchers performed an internally self-consistent assessment by using projections from a single global climate model to assess impacts in all three sectors.

1.3 Report Organization

Chapters 2, 3, and 4 present results for potential climate change impacts on electricity generation in California from solar, wind, and hydropower, respectively. Chapter 5 is a brief synthesis discussion of the combined effects of climate change on electricity production from the three weather-dependent resources. Chapter 6 reiterates overall conclusions of the study. The appendices (from Madani et al. 2008) describe specifics of the hydroelectric power production model adopted for this study and contain a set of figures referenced in the text

CHAPTER 2:
Solar Power

2.1 Summary

The researchers assessed the impact of climate change on the ability to produce electricity from sunlight in California. Two simulations performed with a fine-resolution configuration of Version 3.0 of the National Center for Atmospheric Research (NCAR) Community Atmospheric Model (CAM)[1] global climate model were analyzed for this purpose. In addition, researchers analyzed coarser-resolution simulations from 14 models performed for the *IPCC Fourth Assessment Report*[2] and archived at LLNL's Program for Climate Model Diagnosis and Intercomparison (PCMDI)[3]. The NCAR CAM3 simulation of 1979-2000 has significant biases in simulated downwelling solar fluxes, compared to observations from the National Solar Radiation Database (NSRDB)[4]. These are caused primarily by insufficient scattered sunlight, a consequence of the lack of representation of locally generated scattering particles and coastal fog in the model. Both the NCAR CAM3 simulations and the coarser-resolution simulations in the Intergovernmental Panel on Climate Change (IPCC)[5] archive show minimal changes in downwelling solar fluxes between the historical reference period (1979-2000) and the middle of the 21st century (2040-2060). Although projected changes are small (at most a few percentage points), they do have a high degree of statistical significance and, furthermore, are consistent among the coarse-resolution simulations and between these simulations and the fine-resolution CAM3 results. These findings indicate that climate change will have no significant impact on the ability to generate electricity from sunlight in California.

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[1] NCAR CAM3 refers to version 3.0 of the National Center for Atmospheric Research's Community Atmospheric Model. It is the fifth generation comprehensive 3-dimensional atmospheric global climate model designed for analyzing and understanding global climate. Additional information is available at http://www.cesm.ucar.edu/models/atm-cam/.

[2] IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

[3] See http://www-pcmdi.llnl.gov/.

[4] See http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/.

[5] The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. The IPCC is a scientific body under the auspices of the United Nations (UN). It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data or parameters. See http://www.ipcc.ch/.

2.2 Introduction

This chapter examines the projected impact of climate change on the potential for producing electricity from sunlight in California.

2.3 Method

The ability to generate electricity from sunlight depends on downwelling solar fluxes near ground level. Photovoltaic systems can use both direct and diffuse radiation; concentrated solar collectors in general capture only "direct" (normal beam) radiation. Thus, both direct and total downwelling fluxes are relevant to solar electricity generation, and both were evaluated here.

The impact of climate change on the ability to generate electricity from solar installations in California was assessed using simulations performed with global climate models. First, high-resolution simulations were used for the North American Regional Climate Change Assessment Program[6] (NARCCAP). These simulations were performed with Version 3.0 of the NCAR CAM, hereafter referred to as CAM3.

Algorithmic, computational, and scientific aspects of the CAM3 model have been thoroughly described elsewhere (Collins et al., 2004)[7]. This is the fifth generation of the NCAR atmospheric GCM. The model has 26 levels in the vertical with the top of the model at 3.5 hPa. The time step for the physical parameterizations is one (1) hour. Researchers used the finite volume (FV) method to represent the dynamics of the horizontal structure of prognostic variables: the default horizontal grid size is 2.0° in latitude and 2.5° in longitude. For NARCCAP, a version of this model using fine spatial resolution was developed and run. This version uses horizontal grid spacing of 0.5 deg. in latitude by 0.625 deg. in longitude. At the latitude of California, the horizontal grid size is about 50 km. The principal work in developing this version was the adjustment of parameter values to optimize the simulated climate at fine resolution. In addition, fine-resolution versions of input data sets (specifying land-surface types, and so forth) were prepared.

The simulations analyzed here were performed using prescribed lower boundary conditions on the atmosphere, that is, prescribed sea-surface temperatures (SSTs) and sea ice extents. For the baseline, or control simulation, observed monthly mean SSTs and sea ice concentrations for 1979-2000 were used (ref. PCMDI). For the future-climate simulation, SSTs and sea ice extents were prepared based on a simulation of the A2 greenhouse gas emissions scenario performed with a coarse-resolution version of the NCAR Community Climate System Model an ocean-atmosphere-sea ice model that uses the CAM3 model as its atmospheric component. These SSTs

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[6] The North American Regional Climate Change Assessment Program (NARCCAP) is an international program to produce high resolution climate change simulations in order to investigate uncertainties in regional scale projections of future climate and generate climate change scenarios for use in impacts research. NARCCAP is funded by the U.S. Department of Energy and the National Science Foundation. See http://www.narccap.ucar.edu.

[7]http://www.ccsm.ucar.edu/models/atm-cam/docs/description/

consist of the predicted SST response of the model to increase greenhouse gases, added to observed SSTs. This approach thus applies a first-order bias correction to the simulated SSTs of the model. The period simulated in this future-climate simulation is 2041-2060.

To assess the robustness of conclusions based on CAM3 results, the researchers also analyzed results of simulations archived in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel dataset.

2.4 Evaluation of Simulated Solar Fluxes

The research team evaluated ground-level solar fluxes simulated by the high-resolution CAM3 model against observed values from the National Solar Radiation database (NSRDB)[8]. The basic database includes hourly values of direct, diffuse, and total (direct plus diffuse) solar fluxes, measured at eight locations in California, for 1961-1990. Hourly simulated fluxes from CAM3 were evaluated for the overlap period with the NARCCAP control simulation (1979-1990). Results of this evaluation are summarized in Tables 1 - 3.

Table 1: Characteristics of NSRDB Observing Stations in California

	Latitude	Longitude	Elevation (m)
Arcata	N40 59’	W124 06’	69
Bakersfield	N35 25’	W119 03’	150
Daggett	N34 52’	W116 47’	588
Fresno	N36 46’	W119 43’	100
Long Beach	N33 49’	W118 09’	17
Los Angeles	N33 56’	W118 24’	32
Sacramento	N38 31’	W121 30’	8
San Diego	N32 44’	W117 10’	9
San Francisco	N37 37’	W122 23’	5
Santa Maria	N34 54’	W120 27’	72

Table 1 summarizes properties of the observing station locations. The stations span the full range of latitudes in California, and represent both inland and coastal sites. None is in a high-elevation location; however it is unlikely for a variety of reasons that a large-scale solar power installation would be sited at high elevation, so this omission is not serious for our purpose.

[8] http://rredc.nrel.gov/solar/old_data/nsrdb/

Table 2: Comparison of Simulated vs. Observed Time-Mean Solar Fluxes

	direct model	direct obs	direct bias	diffuse model	diffuse obs	diffuse bias	total model	total obs	total bias	% diffuse obs	% diffuse model
Arcata	147.0	87.7	59.3	36.0	75.6	-39.6	183.0	163.3	19.7	46	20
Bakersfield	220.4	144.4	76.0	30.0	69.2	-39.2	250.4	213.6	36.8	32	12
Daggett	225.8	181.7	44.1	30.4	57.2	-26.8	256.2	238.8	17.4	24	12
Fresno	213.6	143.2	70.4	27.4	70.8	-43.4	241.0	214.0	27.0	33	11
Long Beach	220.7	132.2	88.5	30.7	75.2	-44.5	251.4	207.4	44.0	36	12
Los Angeles	220.7	130.1	90.6	30.7	77.4	-46.7	251.4	207.5	43.9	37	12
Sacramento	201.9	140.8	61.1	27.6	64.9	-37.3	229.4	205.7	23.7	32	12
San Diego	221.2	138.9	82.3	32.1	71.4	-39.3	253.3	210.3	43.0	34	13
San Francisco	162.4	129.1	33.3	38.6	67.5	-28.9	201.0	196.6	4.4	34	19
Santa Maria	211.8	148.9	62.9	31.4	66.8	-35.4	243.2	215.7	27.5	31	13
Mean of 10 stations	204.6	137.7	66.9	31.5	69.6	-38.1	236.0	207.3	28.7	34	14

(All flux values are in W/m^2. Simulated values for Long Beach and Los Angeles are identical because the two cities are located in the same model grid cell.)

Despite the diverse locations of the NSRDB stations in California, biases in the CAM3 solar fluxes are generally similar at all locations (Table 2): direct and total fluxes are overestimated, while diffuse fluxes are underestimated. These errors are all consistent with the model having less-than-observed quantities of scattering materials in the atmosphere. These materials include particulate pollution, which is important in congested areas such as Los Angeles and Long Beach, and agricultural sites such as Fresno. These locally produced particulates are not treated in global climate models, including the one used here. Coastal fog, which is not well simulated in climate models, is an important scatterer in Arcata and San Francisco. Fog is difficult to simulate, however, (for example, Lundquist and Bourcy, 2000) so direct projections of climate change-induced changes in fog would lack credibility. There is reason to believe, however, that coastal upwelling off California may increase with climate change. While this might affect fog properties, the meteorology of fog formation and dissolution is sufficiently complex that one cannot anticipate impacts on fog without quantitative modeling.

Simulated total fluxes at NSRDB stations are too low because a portion of scattered sunlight is reflected into space. Hence, model errors in direct and diffuse fluxes tend to cancel but do not cancel completely.

Table 3: Correlation Coefficients (CC) and Mean Absolute Differences (MAD) Between Hourly Observed and Simulated Solar Fluxes

	CC direct	CC diffuse	CC total	MAD direct	MAD diffuse	MAD total
Arcata	0.55	0.62	0.80	137.3	60.5	101.4.
Bakersfield	0.82	0.61	0.90	132.2	53.7	101.6
Daggett	0.83	0.55	0.91	116.5	44.9	92.9
Fresno	0.83	0.60	0.90	125.9	58.8	95.7
Long Beach	0.68	0.60	0.84	135.0	57.6	103.4
Los Angeles	0.78	0.60	0.90	145.3	64.0	105.0
Sacramento	0.83	0.63	0.90	118.6	50.3	92.4
San Diego	0.76	0.59	0.90	142.8	57.9	107.4
San Francisco	0.67	0.61	0.82	123.7	50.5	98.8
Santa Maria	0.80	0.57	0.90	127.0	53.5	97.3
Mean of 10 stations	0.76	0.60	0.88	130.4	55.17	99.4

2.5 Projected Changes in Ground-Level Solar Fluxes

As noted above, large-scale solar electricity generators use either direct or total (direct plus diffuse) ground-level solar fluxes. In this section projected changes in those fluxes in California were assessed, as simulated by a number of global climate models.

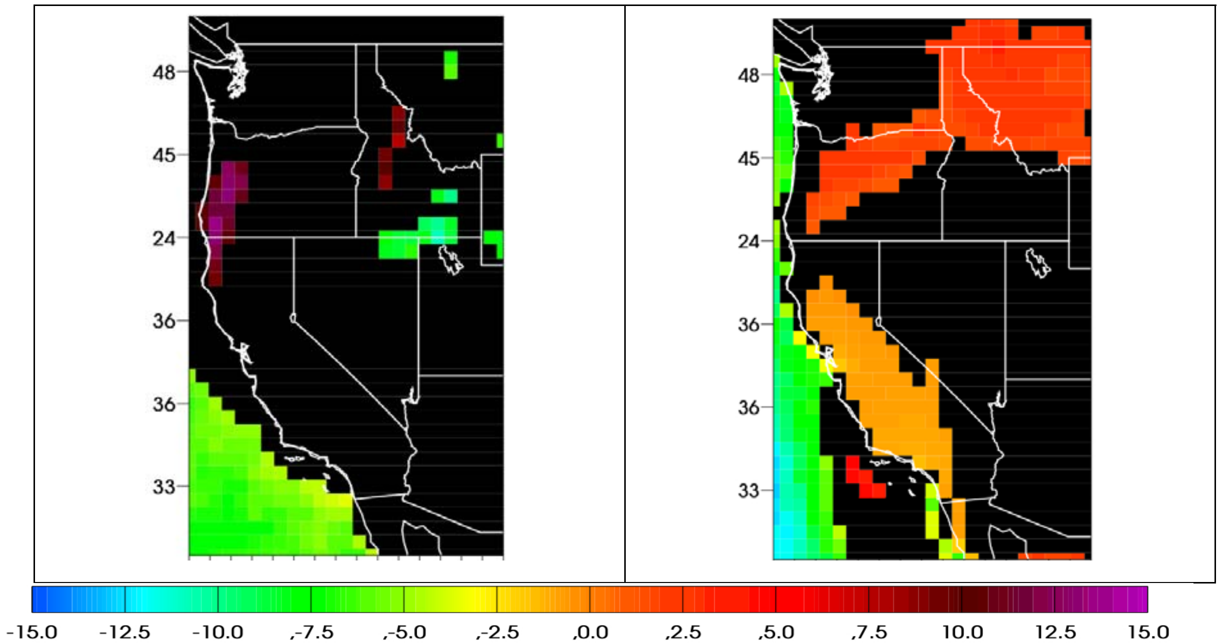

Figure 1: Projected Changes in Total (Direct Plus Diffuse; All Wavelength Ranges) Solar Flux at Ground Level, 2041-2060 Minus 1979-2000.

The images in Figure 1 were created from two simulations performed with the NCAR CAM3 global climate model. Changes are shown as a percentage of the overall mean for the two periods. Left: winter (December-January-February). Right: summer (June, July, August). Results for 2041-2060 assume the IPCC SRES A2 greenhouse gas emissions scenario (a relatively rapid buildup of atmospheric greenhouse gases). Regions shown in black have no statistically significant change between 1979-2000 and 2041-2060 (95 percent confidence). This is determined by comparing differences in mean values for the two periods to year-to-year-variability, using a two-sided Student's t-test. In winter, the model predicts no statistically significant changes in solar fluxes virtually everywhere in the State. In summer, predicted changes are statistically significant in most of the State, but they are very small (about 1 percent). Thus, this model predicts no significant impact of climate change on the ability to generate electricity from the sun in California.

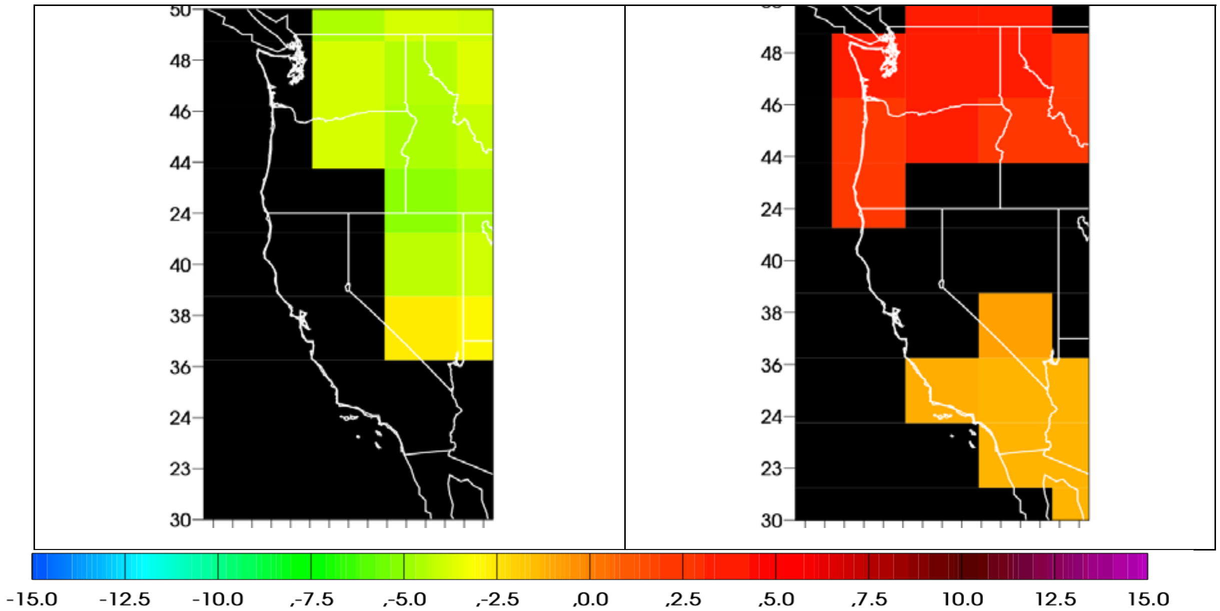

Figure 2: Projected Total Solar Flux Variation at Ground Level, 2041-2060 minus 1979-2000, Multimodel Mean Result

Figure 2 uses the combined data of 14 Global Climate Models that contribute to the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) Multi-Model Dataset.[9] Results were interpolated to a common horizontal grid before averaging.) These models treat the ocean, atmosphere and sea ice, in contrast to the model used to generate results shown in Figure 1, which treats only the atmosphere and is driven by prescribed ocean temperatures and sea-ice extents. As in Figure 1, regions shown in black have no statistically significant change in solar flux. Predicted changes in solar fluxes shown here are similar to those shown in Figure 1 from the high-resolution CAM model.

[9] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

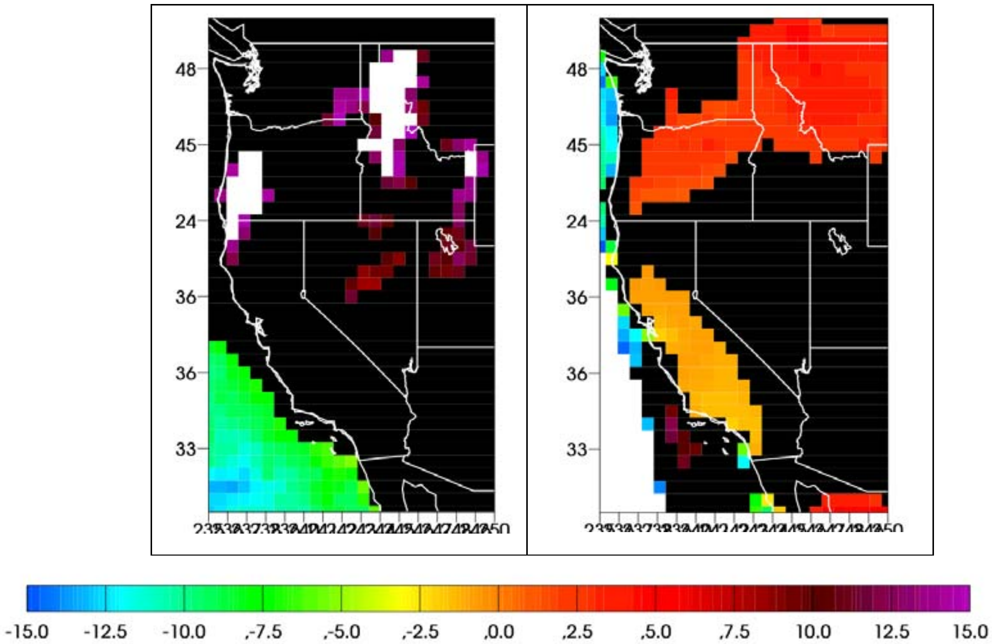

Figure 3: Projected Variation in Direct Component of Solar Radiation from 1979-2000 to 2014-2060.

2.6 Conclusions (Solar Power)

Results from global climate models show biases in simulated ground-level solar fluxes that are consistent with underrepresentation of atmospheric scattering. This means higher-than-observed direct solar fluxes at ground level and lower-than-observed scattered and total fluxes. The simulated fraction of scattered downwelling solar radiation ranges from roughly 3x to roughly 2x less than observed at the NSRDB stations in California.

Simulated responses of downwelling solar fluxes to climate change are small. Simulations with a fine-resolution version of CAM3 show essentially no locations in California where projected changes in wintertime total or direct fluxes have statistical significance at the 95 percent confidence level. In summer, simulated changes reach this confidence threshold in much of the State, but the changes are very small (about 1 percent). Analysis of simulations contributed to the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel dataset show results that are broadly similar to the high-resolution CAM3 results. Thus, there is consensus among climate models for very small effects of climate change on ground-level solar fluxes in California.

CHAPTER 3:
Wind Power

3.1 Introduction

A changing climate may bring increases or decreases in mean wind speeds, as well as greater or lesser variation wind speeds. These changes could make long-term planning for wind energy purposes problematic. Some regions where continued wind development is occurring, such as California and the Great Plains, may be especially susceptible to climate change because the wind regimes of these regions are dominated by one particular atmospheric circulation pattern. Thus, understanding climate change on local and regional scales is key to sustaining the reliability of long-term wind resource assessments in the coming decades.

Historical wind measurements reveal very little about the impacts of anthropogenic climate change (Klink 2007; Pryor et al 2006). Analysis of long-term United States climate station wind speed observations shows a small negative trend (about -0.1 m/s/decade; see Figure 4).

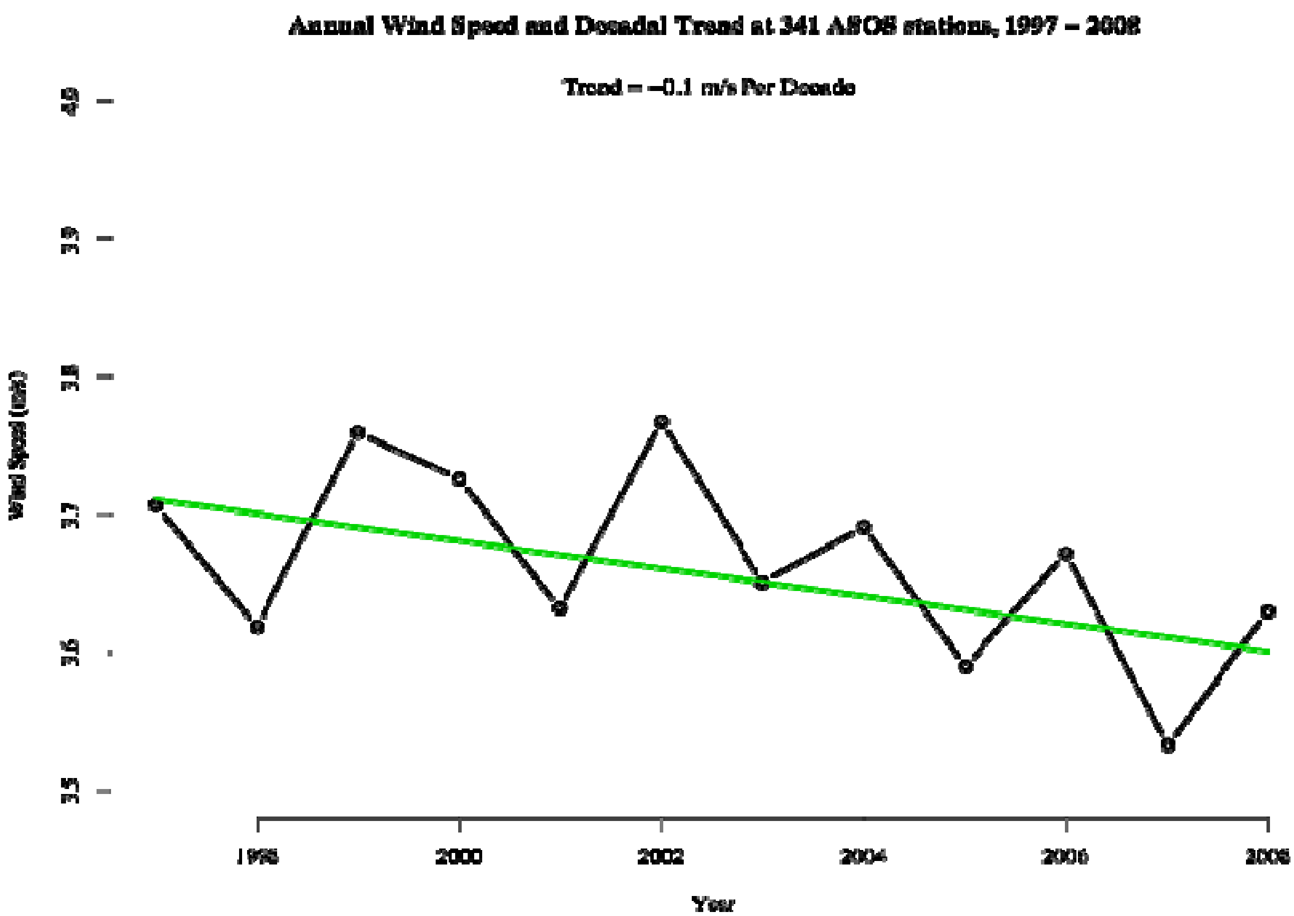

Figure 4: Annual wind speed (m/s) and decadal trend at 341 ASOS stations, 1997-2008

Individual stations show statistically significant increases or decreases in wind speed during this time; however, nonclimatic factors such as changes in local land cover, instrument continuity, or station location moves may be responsible. In addition, decadal timescale natural climate variability could, in principle, produce trends similar to those observed. Wind speeds above the boundary layer (that is, above 1500 m) show a definite positive trend throughout North America during the last 20 years (Figure 5; see Freedman and Zack [2007]). However, this trend follows a general decrease in wind speeds observed during the previous two decades. Whether these represent natural fluctuations or are a manifestation of anthropogenic climate change remains an open question.

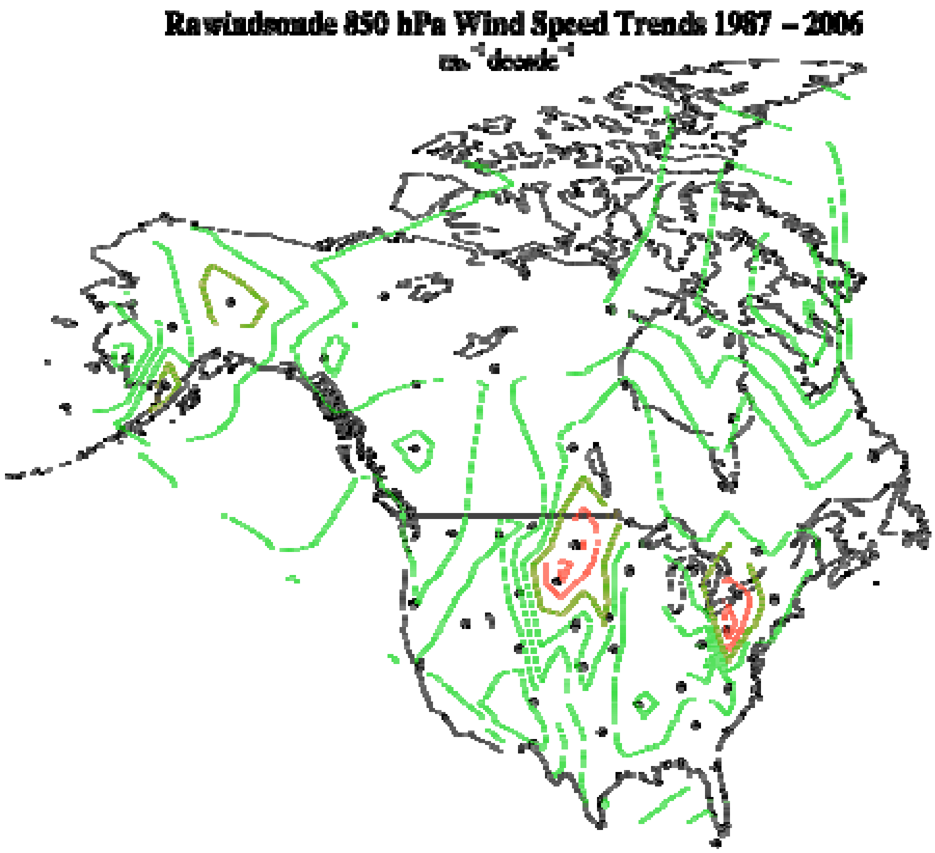

Figure 5: 850 hPa Wind Speed Trends (m/s/decade) for 1987-2006 Over North America.

3.2 Climate Change Study

The research team performed mesoscale simulations of present (1980 - 1999) and future (2041-2060) climate to estimate effects upon wind power production under the IPCC A2 greenhouse gas emissions scenario.[10] Output from high-resolution (50 km) global climate simulations conducted at LLNL for the Department of Energy (DOE) National Science Foundation (NSF)-funded North American Regional Climate Change Prediction Project (NARCCAP) was used to initialize AWS Truewind's Mesoscale Atmospheric Simulation System (MASS) [11]. As set forth in the final scope of work, the following tasks were carried out:

- Task 1: Simulate the present wind climate (1979-1999) in the Tehachapi Pass area using MASS, driven by meteorology from the present-climate simulation. Electricity production is estimated assuming both historical and future projected installed capacity.
- Task 2: Simulate future wind climate (2040-2060) and changes in potential wind power production using MASS, driven by meteorology from the future-climate simulation. Electricity production is estimated assuming both historical and future projected installed capacity.
- Task 3: Assess potential impacts of climate change on wind power generation by analyzing the results of Tasks 1 and 2.

The study area is the wind-resource-rich Tehachapi Pass region of southwestern California, where the primary mechanism driving favorable "gap" winds is the temperature difference between the San Joaquin (or Central) Valley and the Mojave Desert. Wind speeds are generally highest during late spring and early summer afternoons in this area because of the increasing temperature (and pressure) gradient between the rapidly heating Mojave Desert to the south and east and the relatively cooler (and sometimes irrigated) surface of the San Joaquin Valley to the northwest[12]. (Other gap winds in coastal California are generated through land-sea temperature differences analogous to local sea breezes. The cooler surface-layer air in the San Joaquin Valley may also be the result of a remnant marine layer advected inland during previous days.) These temperature contrasts are reduced during the late summer and early fall, hence the lower wind speeds observed at this time.

3.3 Methodology

Simulations covering the entire state, with a grid size of 15 km (Figure 6), and "inner nests" with finer resolution (4-km) centered on Tehachapi Pass (Figure 7) were carried out. To reduce

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10 Under this scenario globally averaged carbon dioxide (CO_2) concentration increases from 350 ppm in 1990 to 500 ppm in 2050.

11 Manobianco, J., J. W. Zack and G.E. Taylor, 1996: Workstation-based real-time mesoscale modeling designed for weather support to operations at the Kennedy Space Center and Cape Canaveral Air Station. Bull. Amer. Meteor. Soc., 77, 653-672. Embedded equations are described in Zack, J., et al., 1995: MASS Version 5.6 Reference Manual. MESO, Inc., Troy, NY.

12 Whiteman, C. D., 2000: *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press. 355 pp.

computational demands while maintaining statistically significant and representative results, the MASS 4-km simulations were performed every tenth day for both the historical and future scenario runs. This configuration produced 727 24-hour cycles for each 20-year run with a wind speed uncertainty (defined here as the standard error of the mean) of ± 2 percent [or about 0.13 m s^{-1}] in the vicinity of Tehachapi Pass).

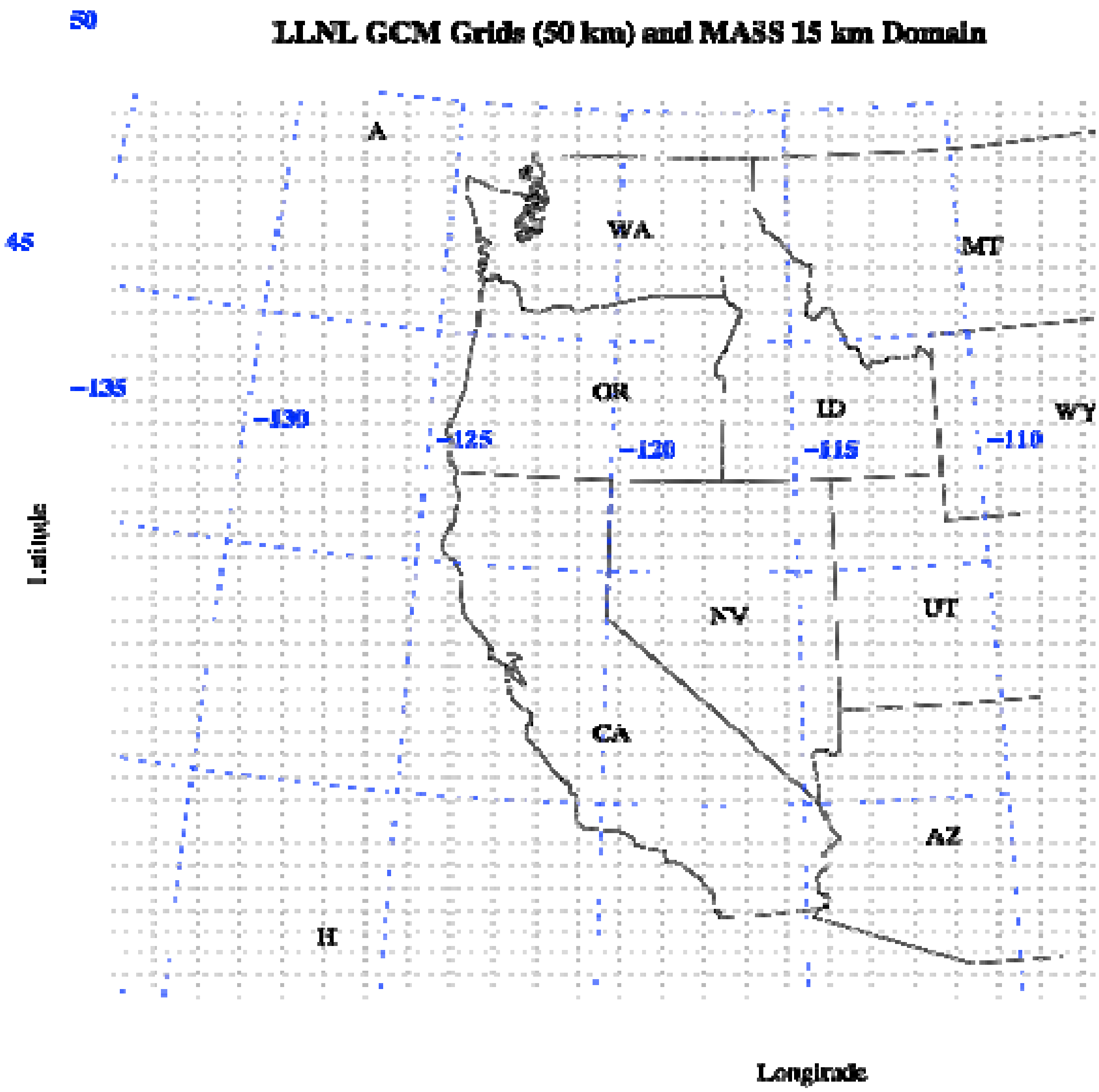

Figure 6: LLNL GCM 50-km Grids (Grey Dotted Lines) Overlain on MASS 15 km Domain

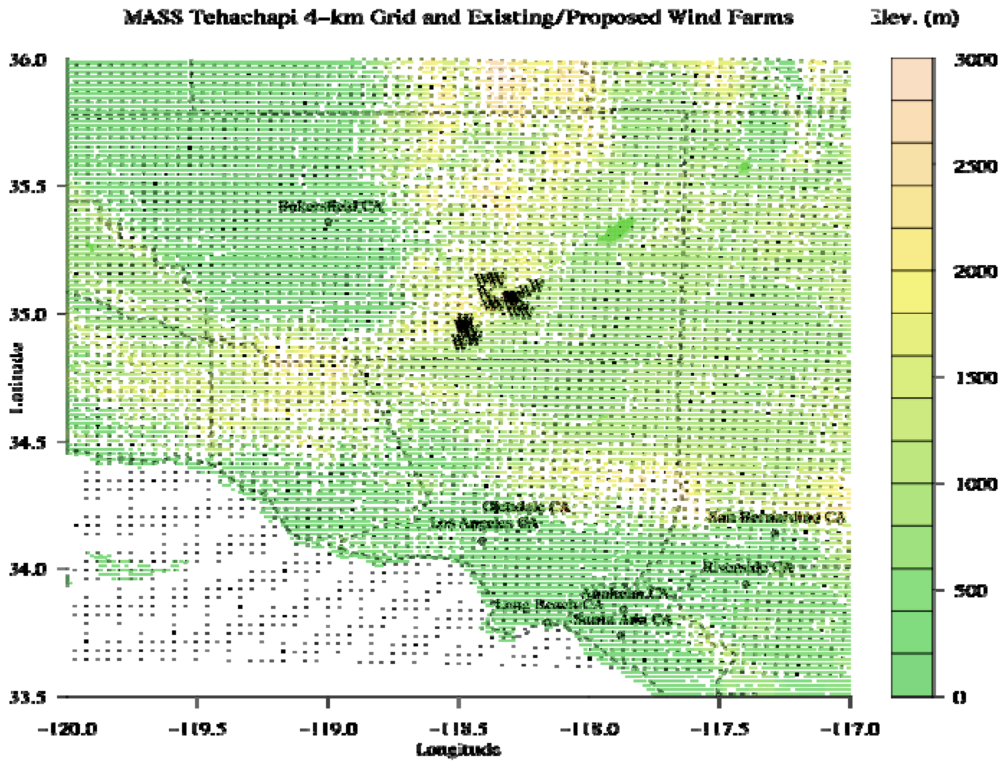

Figure 7: MASS 4-km Grid Centered Over Tehachapi Pass Region.
(W's represent locations of existing and proposed wind farms)

3.4 Results

3.4.1 Present Climate (1980 – 1999)

Model-based projections of future changes must be interpreted in the context of the ability of the model to reproduce relevant observations. The MASS historical simulations generally capture the pattern and magnitude of observed wind speed distributions (Figure A1) with some notable local variation (Figure A2). When comparing long-term tall tower measurements with the nearest MASS 4-km grid point, there are significant discrepancies in the seasonal and diurnal patterns (Figures A3-A8). This may be partially attributable to different periods of records (POR) used in the comparison (2003 - 2008 for the tall tower used in Figures A3-A8, and 1980 - 1999 for the climatology simulation). Moreover, an internal study by AWS Truewind (K. Waight, personal communication) showed that not accounting for irrigation in the Central Valley results in a reduction of wind speeds in the Tehachapi Pass area of about 0.5 m/s, which may explain some of the difference between tower climatology and model climatology. However, even accounting for the soil moisture issue, MASS still has problems simulating the diurnal wind patterns in and around Tehachapi (Figures A4-A8).

3.4.2 Future Climate (2041 – 2060)

3.4.2.1 Spatial Distribution

Qualitatively, the spatial distribution during the future scenario period is quite similar to that of the historical run, indicating that the atmospheric circulation patterns—not necessarily the intensity—do not change appreciably. However, there is an overall decline in wind speeds (Figure A9) throughout the MASS 4-km domain compared with climatology, resulting in most areas showing a 5 - 10 percent decrease in wind power availability (Figure A10), defined here as:

$$P = \frac{1}{2}\rho U^3$$

Where P is the power (W m^{-2}), ρ is the ambient air density (= 1.212 kg m^{-3}), and U is the wind speed (m s^{-1}).

The only relatively windy areas (Class 5 or above) to experience a net increase in available wind power (10 - 20 percent), are in the vicinity of Simi Valley and to the windward side of the mountains north of San Bernardino (Figure A10). The area in the immediate vicinity of the existing Tehachapi wind farms indicates an equivalent 10 - 15 percent decrease in available wind power, but areas just to the WNW show a corresponding increase in available power (although wind speeds are much lower in this area).

3.4.2.2 Temporal Distribution

Although there is an overall decrease in average wind speed at in and around Tehachapi, it is not evenly distributed throughout the year or throughout the day. During April - June, when wind speeds tend to be highest, there is little change in the availability of potential wind power, while during all other months, especially during the fall months (September - November) there is a significant decrease (-0.67 ± 0.14 m s^{-1}) in wind speeds. The diurnal variation also shows uneven changes, with large decreases again noted during the cool seasons (Figures A5 and A8).

These seasonal differences may be a reflection of the relative strength of the primary mechanism responsible for the generating the local high wind speeds observed in the Tehachapi region: the San Joaquin-Mojave Desert pressure/temperature gradient. Under the future climate scenario, the pressure gradient is about 0.1 hPa greater during the spring month's season owing to increased warmth over the Mojave Desert (Figure A11). (Changes in the larger scale pressure distribution may also be superimposed over the local circulation; however, the strength of the winds through Tehachapi Pass is generally governed by the local pressure gradient.) Overall, however, the pressure gradient shows a 0.2 hPa decrease, with the largest decrease in gradient observed during the fall months (Figure A12). One possible reason for the seasonally driven pressure gradient changes may be model estimates of soil moisture referred to earlier. As for the other regions experiencing a net increase in wind speeds (principally the coastal areas near and south of Oxnard), an enhancement of the sea breeze circulation is possible, consistent with findings from other recent studies (Lebassi et al 2009).

3.5 Conclusions (Wind Power)

The local circulation between the San Joaquin Valley and the Mojave Desert is the key mechanism responsible for maintaining the robust winds observed in the Tehachapi Pass area. This model study indicates that significant decreases in wind speed (2 - 4 percent or more) and power potential (10 - 15 percent) are forecast to occur in the immediate vicinity of Tehachapi, the exception being the windier spring months, when an enhanced pressure/temperature gradient further energizes the flow through Tehachapi Pass.

CHAPTER 4: Hydropower

4.1 Introduction

Numerous modeling studies, starting with Gleick (1987), have predicted that anthropogenic climate change will have significant impacts on the natural hydrology of California, with implications for water scarcity, flood risk, and hydropower generation. The best-known of these impacts are straightforward consequences of increased temperatures: a reduced fraction of precipitation falling as snow, reduced snow extent and snow-water equivalent, and earlier melting of snow. An increased fraction of precipitation as rain in turn results in increased wintertime runoff and river flow; earlier and reduced snowmelt results in reduced late-season runoff and river flow. Despite the well-known lack of consensus among global climate models about future changes in annual California precipitation amounts (for example, Dettinger, 2005), the effects just mentioned are robustly predicted (for example, Maurer and Duffy, 2005) because they result from warming, about which there *is* consensus. Confidence in these predictions is increased by observational studies that show these changes to be underway (for example Stewart *et al.*, 2005), as well as by studies involving both observations and modeling that indicate that observed changes in western U.S. hydrology are too rapid to be explained entirely by natural causes (for example, Maurer *et al*, 2007; Barnett *et al*, 2008).

As noted above, one possible consequence of human-caused changes in mountain hydrology in the western United States is changes in hydropower production, especially from high-altitude facilities on watersheds that have historically been snow-dominated. This concern is especially acute, since a majority of the state's hydropower is produced in facilities of this type. Furthermore, as noted by Madani and Lund (in review), these high-elevation facilities have relatively little storage capacity, implying limited capability to adapt to changes in climate.

One can imagine that a shift toward earlier-in-the-year snowmelt and runoff would tend to produce similar changes in the timing of hydropower generation. In particular, in the absence of adequate storage capacity, it might become difficult to produce power at the end of the dry season, when demand for electricity can be very high. On the other hand, a large enough reservoir could store enough water to effectively buffer this problem and allow power generation throughout the dry season. Hence, intuition suggests that the effects of climate change on hydropower generation will depend strongly on the properties of the generation system, in particular, reservoir size. Furthermore, of course, these effects will depend on altitude, being greatest at intermediate altitudes where slight warming will raise the temperature above freezing. Watersheds that are already rain-dominated, or are well below freezing, will not exhibit the effects discussed here in the near future.

Of course, besides issues of seasonal timing, a significant increase or decrease in annual total precipitation would be an important benefit or detriment (respectively) to hydropower generation.

The published literature largely supports this picture. Vicuna e*t al*. (2008) used a linear programming (LP) optimization model to study effects of climate change on the 11 hydropower systems in the Upper American River. Two climate change scenarios each simulated by two general circulation models (GCMs) were used to drive the LP model. Perhaps the most interesting results in this study are from sensitivity tests in which the capacity of storage reservoirs was arbitrarily increased or decreased. This exercise showed that with large storage capacities, the rate of energy generation largely follows pricing changes (because the system holds onto water until prices are high), whereas in the limit of small storage capacity, the timing of energy generation tracks the unimpaired flow rate.

A study by Madani and Lund (2009) used a more idealized model that simulates 137 of the 156 high-elevation plants identified in the State; thus, the model trades some degree of fidelity for comprehensiveness. This approach makes assumptions (characterized as the "No Spill Method" and discussed below) that allow these systems to be modeled in the absence of specific information (such as heads, storage capacities, and so forth) about the physical properties of individual systems (Madani and Lund 2009). A comparative study (Madani et al. 2008) showed that this approach produces results that are generally similar to those of a more detailed model, when similar assumptions about pricing are made.

Madani and Lund (2009) looked at hydropower generation in 137 high-elevation systems under three simple climate change scenarios: wet, dry, and warming only. It found that existing storage capacity is sufficient to largely compensate for expected changes in the seasonal timing of snowmelt, runoff, and river flow. A hypothetical decrease in annual total runoff, however, translates more directly into a corresponding reduction in energy generation. The predicted response to a hypothetical increase in annual runoff, however, is not symmetrical: this scenario results in increased spill and very little increase in energy production.

The Energy-Based Hydropower Optimization Model (EBHOM) (Madani and Lund 2009) was used to estimate hydropower impacts of the same future climate scenario considered in other sections of this study.

4.2 Method

4.2.1 Overview

This study used a sequence of models to simulate effects of climate change on hydropower generation in California. This sequence is described in brief here, and each model is discussed in more detail immediately below.

As with many societal-impacts studies, researchers started with a global ocean-atmosphere general circulation model (OAGCM). This simulates the fundamental physics of the climate system (the atmosphere, ocean, and sea ice) and its response to increased greenhouse gases. From this model, a historical reference period (1979-2000) and a future period (2041-2061) were taken, which was simulated assuming the SRES "A2" greenhouse gas emissions scenario. While this model captures present understanding of climate system physics, it represents this physics on a spatial scale that is too coarse for the research team's purposes. (The grid spacing is approximate 1.4° in latitude and longitude.) The climate simulated by this model was therefore "downscaled" to a ~50 km grid using a fine-resolution global-domain atmospheric climate model. The fine-resolution atmospheric model simulates full atmospheric physics and dynamics, based upon sea surface temperature and sea ice extents (that is, lower boundary conditions) from the OAGCM. Although significantly finer in resolution than the OAGCM, the resolution of this model is still too coarse to adequately represent California mountain hydrology. In particular, the mountain topography is smoothed, resulting in overly warm surface temperatures and insufficient snow cover. To address this issue, further downscaling of temperature results is needed; this was accomplished by means of a commonly used "change factor" approach described below, which produced temperature results on 0.125 ° latitude by longitude (~12 km) grid. Results for other variables were interpolated onto this same grid and then used to drive a model of surface hydrology. This model predicts (among other quantities) snow cover and surface runoff. All of this was done for two time slices: a historical reference period (1979-2000) and a future period (2041-2061). Surface runoff results for these two periods were then used to simulate hydropower generation using EBHOM.

4.2.2 Ocean-Atmosphere Sea-Ice Model

The OAGCM results used in this study were from the National Center for Atmospheric Research (NCAR) and U.S. Department of Energy (DOE) Parallel Climate Model (PCM). These results were archived as part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel dataset.[13] The specific simulation researchers took results from was performed using a model version having modestly enhanced spatial resolution (T85 truncation, corresponding to grid dimensions of about 1.4° in latitude and longitude). This model is described in detail in a special issue of the *Journal of Climate* (Volume 19, Issue 11, June 2006).[14] The specific simulation used represented the SRES "A2" scenarios for greenhouse gas emissions.

4.2.3 Fine-Resolution Atmospheric General Circulation Model

Because finer spatial resolution results for this study was required, sea-surface temperatures (SSTs) and sea ice extents from this simulation were used to drive a fine-resolution global atmospheric general circulation model (AGCM); this computationally intensive exercise was performed as part of the North American Regional Climate Change Prediction Project (NARCCAP).[15] The AGCM used was a fine-resolution version of the National Center for Atmospheric Research (NCAR) Community Atmospheric Model (CAM) Version 3.0. This differs from the publicly distributed versions primarily in using finer spatial resolution; the grid dimensions were roughly 0.5° in latitude and longitude, versus 2.8° in the standard configuration and 1.4° in the version used in the OAGCM results adopted here. Besides

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[13] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php and Meehl et al, 2007

[14] The papers from this issue can be viewed at:
http://www.ccsm.ucar.edu/publications/jclim04/Papers_JCL04.html

[15] http://www.narccap.ucar.edu/

changing the horizontal grid spacing, the high-resolution model version uses finer-resolution topographic input, which is important in reproducing an accurate regional-scale surface climate. In addition, values of key parameters pertinent to cloud parameterizations were iteratively retuned to optimize the simulated climate at the finer resolution.

Rather than driving the fine-resolution AGCM with sea-surface temperatures (SSTs) and sea ice extents directly from the coupled OAGCM (that is, CCSM), a first-order bias correction was applied to the SSTs and sea ice extents:

$$SST_{fut} = SST_{obs} + (SST_{fut}^{ccsm} - SST_{hist}^{ccsm})^{mean}$$

Here, SST_{fut} are the SSTs used to drive the historical and future AGCM simulations, respectively; STT_{obs} are observed monthly mean SSTs, SST_{fut}^{ccsm} and SST_{hist}^{ccsm} are SSTs calculated by CCSM for the future and historical periods respectively, and the superscript "mean" indicates that long-term average values were used to calculate this correction term. A similar bias-correction formulation was used for sea-ice extents. In this approach, the year-to-year variability in the SSTs and sea ice extents used to drive the AGCM are the same as in observations, rather than CCSM; in other words, the bias correction also replaces the year-to-year variability from the ocean-atmosphere-sea ice model with that from observations. For the historical period, the fine-resolution AGCM was forced with observed monthly mean SSTs and sea ice extents for 1979-2001:

$$SST_{hist} = SST_{obs}.$$

4.2.4 Surface Hydrology Model

To simulate hydropower generation in a mountainous region, a better simulation of surface hydrology was required than can be obtained from a global-domain climate model. Researchers also needed finer grid spacing. Even at the relatively fine AGCM grid spacing of 50 km, elevations in mountain regions are truncated, resulting in warm temperature biases. At critical elevations, these biases result in rain when there should be snow, and hence major errors in the seasonal timing of runoff (among other quantities). This would result in very poor simulations of hydropower production.

Output from the fine-resolution AGCM was used to drive the physically based Variable Infiltration Capacity (VIC) model Version 4.0.6 surface hydrology model.[16] The VIC model was developed by Liang et al. (1994). This model has been widely applied to regions in California by Anderson *et al* (2008), Hayhoe *et al.* (2004), and Maurer (2007). The specific model configuration used was the same in Maurer (2007) and was provided courtesy of Prof. Ed Maurer.

The VIC model performs a calculation of the energy (including water) balance in the upper layers of soil. The key quantities simulated are fluxes of energy and moisture at the atmosphere-land interface. For this study, the key output quantity is surface runoff.

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[16] The current version is described and available at: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html.

The model uses prescribed meteorological inputs at daily (as in this case) or subdaily time scales. Although the model can use a variety of grid spacings, the simulations performed used the 0.125° (latitude by longitude) grid spacing that is commonly used in VIC simulations. A key assumption in the model is that each grid cell behaves independently of others, including neighboring cells; that is, there is assumed to be no horizontal flow of energy or moisture.

Vegetation, soil, and elevation data needed to drive VIC were obtained from the Land Data Assimilation System (LDAS).[17] The VIC model needs 11 meteorological input quantities, but the user need not specify all of these; those that are not specified are generated internally by the model. In the simulations performed here, the meteorological variables used to drive VIC were daily mean precipitation, daily mean wind speed, and daily minimum and maximum near-surface air temperatures. These were obtained as described below.

Two simulations with VIC were performed, representing the historical reference period (1979-2001) and the future period (2041-2060). Both simulations were driven with daily-mean precipitation and wind speeds from the AGCM that were interpolated to the 0.125° latitude by 0.125° longitude grid used by the VIC model.

To address the temperature biases of the AGCM mentioned above, researchers applied a simple correction scheme; this was applied after interpolating the AGCM output to the VIC grid spacing of 0.125° in latitude by 0.125° in longitude. By analogy with the SST bias correction above, near-surface temperature values were adjusted as follows:

$$T_{fut} = T_{fut}^{agcm,daily} - (T_{ref}^{agcm} - T_{obs})^{mean}$$

$$T_{ref} = T_{ref}^{agcm,daily} - (T_{ref}^{agcm} - T_{obs})^{mean}$$

The T_{fut} and T_{ref} are temperatures input to the VIC future-period and reference-period simulations, respectively; T_{obs} are observed temperatures from a data set developed by Maurer (2002); T_{ref}^{agcm} are temperatures during the reference period simulated by the AGCM; T_{fut}^{agcm} are temperatures during the future period simulated by the AGCM. In this approach, the day-to-day variability in temperatures used to drive VIC reflects that in the AGCM, not observations. This is important, as it preserved day-to-day correlations between temperature and precipitation that are simulated by the AGCM. As implied above, the main effect of this bias correction was to reduce temperatures in high-elevation regions by allowing better representation of the lapse-rate effect.

As described next, surface runoff values from these two VIC simulations were used as inputs to an optimization model of hydropower generation.

4.2.5 Hydroelectric Power Generation Model

As noted above, hydropower generation in specific watersheds can be simulated using models that incorporate key properties of the watershed and generation infrastructure (for example, Vicuna et al., 2006; Vicuna and Dracup, 2007). Although models of this type are in principle

[17] These are available at: http://ldas.gsfc.nasa.gov/LDAS8th/elevation/LDASelevation.shtml.

superior, they cannot practically be applied to large numbers of installations because the detailed system data (for example, reservoir capacities) needed to configure these high-fidelity models are often not publicly available. Hence, for looking at regionwide hydropower generation, Madani and Lund (2009) developed an alternative modeling approach that can give an approximate assessment of regionwide effects without the need for detailed configuration data for each installation.

This model makes three key assumptions about hydropower infrastructure that allow it to treat large numbers of systems practically. The first is that there is no carryover storage; in other words, reservoirs are empty at the end of the dry season. (Lake Almanor is a notable exception to this general rule.) The second key assumption is "no spill." This means that storage capacities are assumed to be sufficient to prevent spillage at any time *during an average water year*. This does not imply that spillage never occurs, only that the system is designed to prevent spillage during an average year. (The no-spill approach is described in detail in Madani and Lund (2009). Because it is assumed no carryover storage, the no-spill assumption means that the accumulated difference between inflow and outflow never exceeds the reservoir storage capacity. The assumptions of no carryover storage and no spill, taken together, imply that during an average year all runoff entering each reservoir is run through the turbines and produces electricity at some time during the year; under this assumption, reservoir operations determine monthly, but not annual total, generation. Finally, the model of Madani and Lund assumes that storage elevations contribute negligibly to overall head (that head equals penstock height); this allows one to assume a one-for-one relationship between water stored and energy produced; that is, that each cubic yard of water stored produces the same amount of energy.

EBHOM is a nonlinear optimization model that attempts to optimize revenue, taking into account peak and off-peak energy pricing and the nonlinear relationship between generation and revenue (this is described in detail in Madani and Lund 2009).

As noted above, when the same pricing assumptions are made, EBHOM has been shown to produce similar results to those of Vicuna (Madani *et al*., 2008).

Similar to Madani and Lund (2009), important assumptions about natural hydrology were made here. It is assumed that seasonal patterns of runoff depend only on elevation. Thus, for each 1,000-feet "elevation band," a month-by-month pattern of runoff is derived. In this *modus operandi*, altered climates are represented by means of "perturbation ratios," Q, described below. In the present application, surface runoff results from the two VIC simulations sets were grouped into eight elevation bands, each representing a 1,000-foot interval of elevation. A consequence of this approach is that the response of surface runoff to climate change is assumed to be identical for all watersheds within each elevation band. This is justified because this response largely depends on transitions from below-freezing to above-freezing conditions, which depend primarily on elevation. For each elevation band, k, and month, m, grouped surface runoff values from VIC were used to create perturbation ratios, $Q_{k,m}$, which represent the runoff response in elevation band k and month m:

$$Q_{k,m} = \frac{R_{k,m}^{FUT}}{R_{k,m}^{REF}} \quad k = 1,8;\ m = 1,12$$

Here, $R_{k,m}^{FUT}$ is the total surface runoff from all grid cells in elevation band k and month m. $R_{k,m}^{FUT}$ is the analogous quantity for the historical reference simulation. Elevation band 1 corresponds to surface elevations between 1000 and 1999 feet; band 2 is 2000 – 2099 feet, and so on.

These perturbation ratios were then used to drive the EBHOM. Using these perturbation ratios, rather than raw runoff values, to drive the optimization model provides another form of bias correction, in that researchers relied upon the VIC model to simulate the runoff response to climate change, but not the baseline runoff values.

Vegetation, soil, and elevation VIC parameters were obtained from the Land Data Assimilation System (LDAS)[18].[19]

As noted above, no adjustments were made to the AGCM's precipitation values beyond spatial interpolation to the grid of the VIC model. The precipitation data from the GCMF scenario were used directly to drive VIC for the future, predictive runoff. Similarly, wind speeds from the AGCM were used directly to drive VIC, after components were combined into a single value using

$$s = \sqrt{u^2 + v^2}\ .$$

Here s is the resulting daily wind speed, and u and v are the meridional and zonal components, respectively.

4.3 Results

The research team's results for optimized energy generation are driven primarily by large projected reductions in precipitation in the future climate scenario (Figure 8). In the study area, annual mean precipitation in the future period is reduced by as much as 30 percent compared to in the historical reference period. Because of the complex relationships among precipitation, evapotranspiration, and runoff (which are elucidated nicely by Wigley and Jones, 1985), these already-large precipitation decreases produce proportionately larger reductions in runoff and stream flow. In other words, the percentage reductions in runoff and river flow exceed those in precipitation.

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18 NOAA, NASA, *data*, Land Data Assimilation System, http://ldas.gsfc.nasa.gov/LDAS8th/elevation/LDASelevation.shtml, March 10, 2009.

[19] These parameters are publicly available at: http://ldas.gsfc.nasa.gov/LDAS8th/elevation/LDASelevation.shtml.

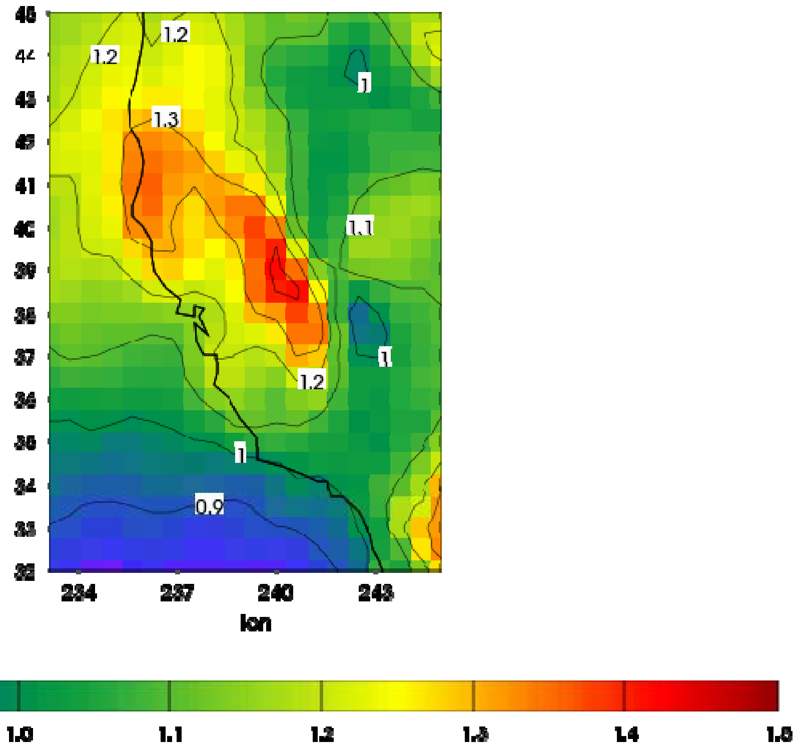

Figure 8: Ratio of Simulated Multiyear Annual-Mean Precipitation in the Historical Reference Period to That in the Mid-21st Century Future Period.
(These results are from the Parallel Climate Model (PCM) global ocean-atmosphere sea ice model, downscaled using a fine-resolution version of the National Center for Atmospheric Research (NCAR) global atmospheric climate model.)

This phenomenon is exaggerated by the tendency for warming to result in increased evaporation. Disproportionate decreases in runoff in a dry future-climate scenario are seen in other modeling studies (for example, Ficklin *et al.* 2009). Jones et al. (2005) investigated changes in runoff in several surface hydrology models in response to a hypothetical 1 percent change in precipitation and found responses ranging from 1.8 percent to 4.1 percent; that is, the percentage response in runoff was anywhere from roughly double to roughly 4x the percentage change in precipitation. Similar values were seen in an observational study by Karl and Riebsame (1989).

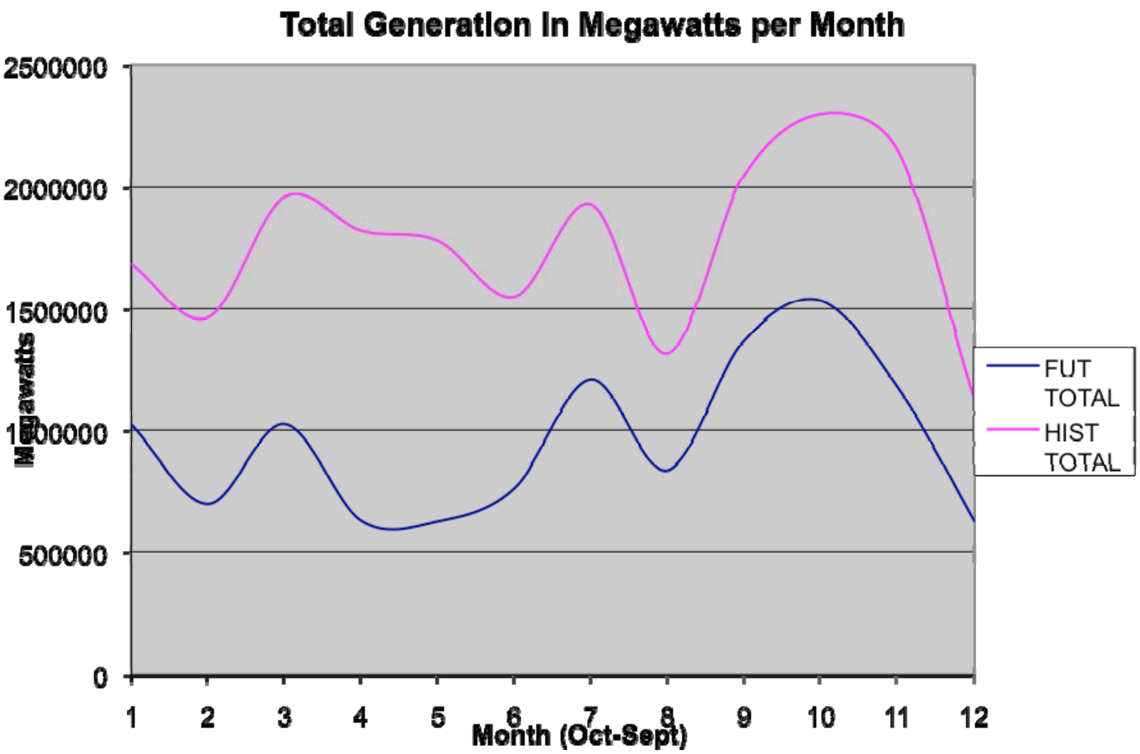

Figure 9: Simulated Regionwide Hydropower Generation in the Historical Reference Period (Top) and During 2041-2061 (Bottom).
(Horizontal Axis is months, starting with October.)

Reduced precipitation and resulting reductions in runoff result in reduced hydropower generation in all months and elevation bands (Figure 9). This reflects the tendency of the selected climate models to simulate a much drier future and is not necessarily representative of results that would have been obtained had other models been selected, or of the actual future in California. As noted by many investigators (for example, Dettinger, 2005), there is no strong consensus among global climate models as to whether California's future will be wetter or drier. While a slight majority of climate models project a drier future for California, the magnitude of precipitation reductions seen here is highly atypical.

These results are consistent with those of Madani and Lund (2008) who examined a "dry" future climate scenario. Like the research team, they found that reductions in annual precipitation result in reduced generation; revenues are also reduced, although by a lesser amount because the model acts to optimize operations and maximize revenue. These results indicate that a future that is both drier and warmer would have important impacts on the ability to generate electricity from hydropower.

CHAPTER 5: Synthesis

5.1 Effects of Climate Change on Potential to Generate Electricity From Wind, Solar, and Hydro Resources in California

Climate change and other considerations create a strong societal motivation to increase production of electricity from renewable resources. This has been expressed through the passage of Renewables Portfolio Standard (RPS) in California and elsewhere. Reaching the targets set by California's RPS involves formidable technical and institutional challenges, which have been widely discussed. Often overlooked in these discussions is the possibility that climate change itself will affect ability to generate electricity from weather-dependent renewable resources, through changes in wind speed, solar fluxes, or hydrology.

This study is among the first to take an integrated look at the effects of climate change on potential ability to generate electricity from wind, solar, and hydro resources in California. The research team's findings must be considered preliminary; in particular, the results for wind power and hydropower are based on a single set of models and should be tested for robustness by reassessment with additional models. (Findings were confirmed for solar power by duplicating the analysis using results from a suite of models.) In addition, wind-power impacts were assessed in only one major generating area (Tehachapi); other regions such as Altamont might have different trends and should be studied.

With those important *caveats* in mind, researchers found that climate change has mildly negative consequences for renewable electricity production in California. Downwelling solar fluxes at ground level—which determine the potential for solar power generation—are predicted to decrease very slightly in the summer season; this would result in a corresponding reduction in solar power production. Although small, this decrease is statistically significant. No statistically significant change in winter-season fluxes were found. To assess the robustness of these findings, researchers repeated the analysis using results from 14 global climate models participating in the Coupled Model Intercomparison Project, Phase 3 (CMIP3) and archived at the Lawrence Livermore National Laboratory. This analysis confirmed the findings from the fine-resolution global climate model. This analysis, thus, constitutes a robust prediction for a small decrease in potential solar electricity generation.

As noted above, this model does not reproduce particularly well the partitioning of downwelling solar fluxes into direct and diffuse components. This is not surprising, as the model does not represent many of the agents that scatter light in the atmosphere. In some cases (for example, aerosols) this is by design; in other cases (for example, fog), this reflects shortcomings in the model.

Results for wind-generated electricity, at least in Tehachapi, also indicate a small decrease in potential power production, again in some seasons only. This result in particular should be considered preliminary, as predicted wind speeds can be sensitive to specifics of the model such as treatment of soil moisture and assumptions about land-use change. Besides reassessment using different climate models (both global and nested), it would be useful to perform studies that quantify the sensitivity of findings to key aspects of the model formulation and model input data (such as land use specifications in the nested model).

The research team's results for wind power apply only to the Tehachapi region and are not readily generalizable to other wind-power producing regions, such as Altamont. For that region, one would expect that predicted increases in interior vs. coastal temperature gradients would result in stronger sea breezes and hence more wind power; on the other hand, at least one analysis indicates that this temperature gradient has *decreased* recently, due to reductions in coastal fog (J. Johnstone, U.C. Berkeley, personal communication). This analysis contradicts an earlier study by Lebassi *et al.*, (2009) that claims that observations show an increasing trend in the strength of the sea breeze. This is an expected consequence of more rapid interior (vs. coastal) warming, a common feature of GCM simulations. Since effects involving fog are not captured in global climate models, it is not clear how much credence to place in the prediction of these models for stronger sea breezes (and hence more potential wind power). Clearly, this is an area where further research is very much needed.

The study findings for hydroelectric power generation (that is, significant reductions) are a consequence of the large predicted reduction in annual mean precipitation in the global climate models used. This finding is hydrologic model-dependent; there is not a strong consensus among the CMIP3 global climate models as to whether California will see an increase or decrease in annual-mean precipitation—although more than half of the models predict a decrease (Cayan et al. 2006). Thus, these results, at least qualitatively, represent the current generation of climate models. The magnitude of precipitation decrease projected by the research team's models, however, is very unusual.

Although the findings are generally pessimistic, they do not necessarily have major implications for the practical ability to produce electricity from these renewable resources, or to meet RPS targets. The decreases predicted in downwelling surface solar fluxes, although statistically significant and robust among climate models, are small enough that they could easily be overcome by increases in installed surface area or in the efficiencies of electricity-producing technologies (for example, photovoltaics). Similarly, the results for wind power apply only to the Tehachapi area and, in any case, show a relatively small decrease in potential power production. Our most worrisome finding is that of reduced hydropower production. This is all the more true because at present hydro is the largest contributor among renewables to electricity production in California. As discussed above, the predicted reduction in hydropower production results from an unusually large projected decrease in annual mean precipitation in the global climate model used. Certainly if such a decrease happened, this would be pessimistic for hydropower production and water supply reliability.

CHAPTER 6: Conclusions and Recommended Future Research

It is unlikely that climate change will significantly affect ability to generate electricity from sunlight in California. This study predicts a very small climate change-related decrease in surface downwelling solar radiation in California; a change of this magnitude, or even larger, could be compensated for by increases in installed capacity or improvements in generation technology.

Effects of climate change on wind-power generation in California are much more uncertain. This study found mildly negative impacts in the Tehachapi region; however, this is based on only one set of models and in any case looks only at one region, albeit an important one. Impacts on wind-power generation in other regions will depend on whether the sea breeze strengthens or weakens as a result of climate change. Because this depends on ocean-atmosphere interactions in regions of complex topography (that is, phenomena such as upwelling and coastal fog), global climate models cannot predict this reliably. Observational evidence on this question is mixed.

Climate change impacts in hydropower are similarly difficult to predict. In this case, the difficulty arises because of substantial uncertainty in changes in annual total precipitation in the region. The climate models used here showed much drier future conditions, which results in reduced hydropower generation. While this is (qualitatively) typical of the results of other global climate models, a significant number of models show wetter future conditions. Narrowing this uncertainty through improving climate models will be difficult. On a larger scale, agreement among climate models regarding future precipitation is quite good for the whole of North America, implying that disagreement in California is a consequence of relatively small differences among models in the location of specific climate features; it is difficult to imagine being able to determine with confidence which models are more reliable in this regard. Similarly, inferring a trend in future precipitation from observations will be very difficult. For one thing, large interannual variability in California precipitation makes trend identification difficult; also, the Pacific Decadal Oscillation[20] can produce multidecadal trends that are difficult to distinguish from an anthropogenic trend.

These considerations suggest that, of the three areas considered here, future research focused on wind power would likely produce the best return on investment. Solar power production is a lower research priority because there is less that was required to learn in climate change

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[20] The Pacific Decadal Oscillation (PDO) is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). As seen with the better-known El Niño/Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in the Pacific Basin and the North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. See http://www.ncdc.noaa.gov/teleconnections/pdo/.

impacts); hydro is also a lower priority because impacts will depend strongly on future changes in annual precipitation, which will likely remain very uncertain for some time.

As discussed above, future potential wind power generation in California will depend on difficult-to-predict changes in regional-scale climate. For example, changes in coastal fog, which is not well represented in global climate models, will influence changes in coastal vs. inland temperature gradients, which are the primary drivers of the sea breeze (the main energy resource for wind power in many regions). Similarly, wind speeds can be sensitive to soil moisture, which is difficult to accurately predict in climate models and, in any case, can be strongly influenced by human activities such as irrigation and other forms of land-use change.

Based on these considerations, the following activities are recommended as future research to improve understanding of potential impacts of climate change on wind-power generation:

- Perform simulations using a fine-resolution coupled ocean-atmosphere model to understand the possible evolution of coastal fog, upwelling, the sea breeze, and related phenomena.
- Quantify the sensitivity of future potential wind power generation to the range of outcomes identified by the above.
- Perform additional simulations to understand the sensitivity of potential wind-power generation to anthropogenic effects other than greenhouse gas emissions, particularly irrigation and other forms of land-use change.
- Analyze observed trends in coastal fog to understand if these result from human activities or natural climate variability.

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Glossary

AGCM	Atmospheric General Circulation Model
ASOS	Automated Surface Observing System
CAM3	Community Atmospheric Model version 3.0
CCSM	Community Climate System Model
CMIP3	Coupled Model Intercomparison Project phase 3
DOE	United States Department of Energy
EBHOM	Energy-based Hydropower Optimization Model
EPA	Environmental Protection Agency
GCM	Global Climate Model or General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
LDA	Land Data Assimilation
LDAS	Land Data Assimilation System
LLNL	Lawrence Livermore National Laboratory
LP	Linear Programming
MASS	Mesoscale Atmospheric Simulation System
NARCCAP	North American Regional Climate Change Assessment Project
NCAR	National Center for Atmospheric Research
NSF	National Science Foundation
NSRDB	National Solar Radiation Database
OAGCM	Ocean Atmosphere General Circulation Model
PCM	Parallel Climate Model
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RPS	Renewables Portfolio Standard
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature

VIC	Variable Infiltration Capacity
WCRP	World Climate Research Programme

Appendix A:

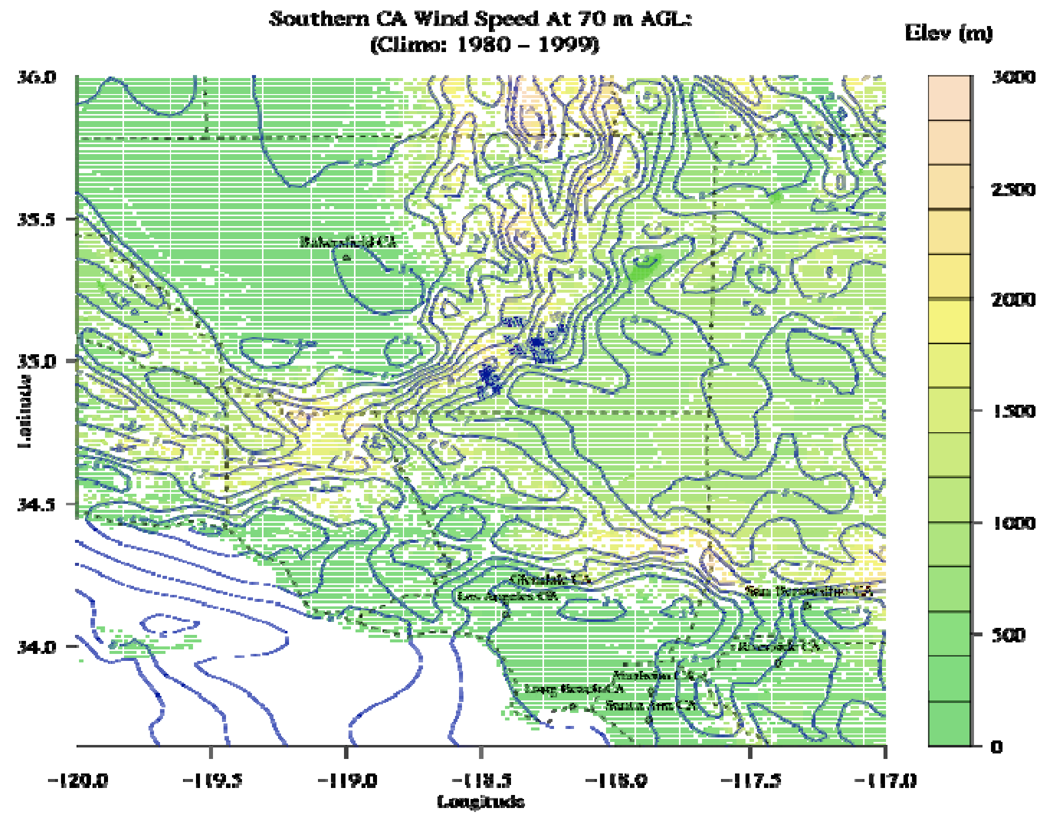

Figure A1: MASS 4-km Climatological (1980 - 1999) Wind Speed (Blue Contours in m/s, W's represent locations of existing and proposed wind farms)

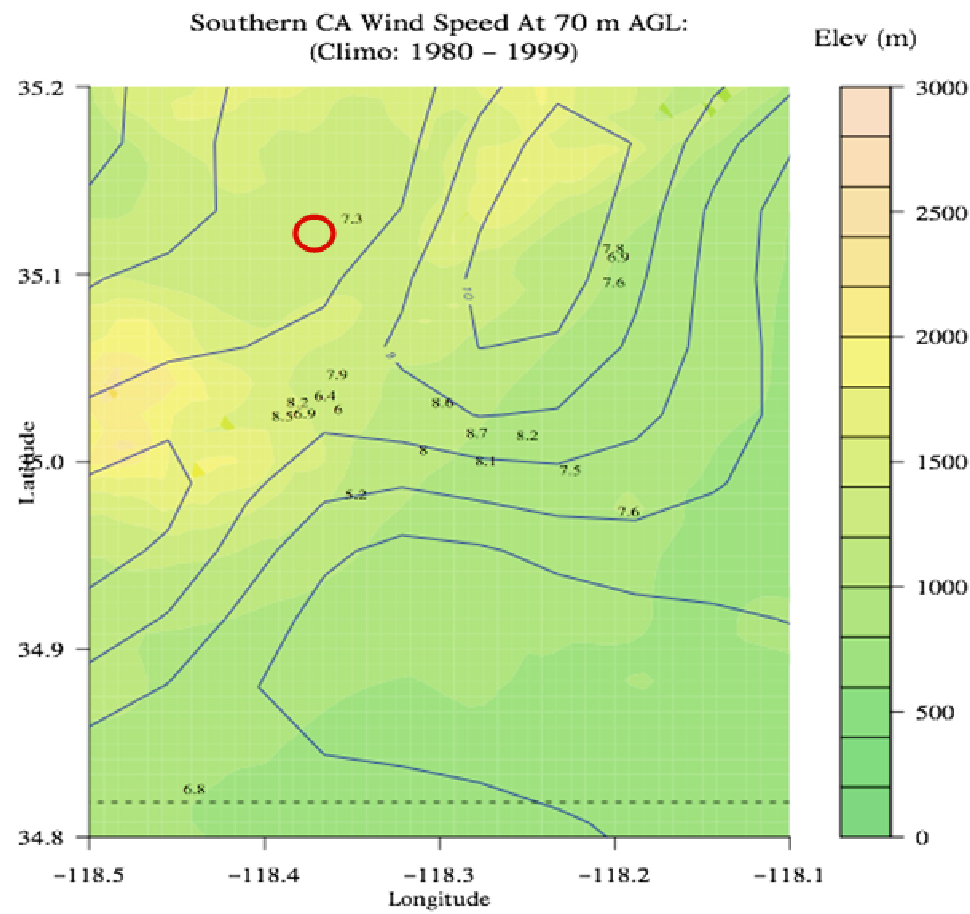

Figure A2: MASS 4-km Climatological (1980 - 1999) Wind Speed (Blue Contours in m/s)
(Numbers represent annualized 70 m AGL average wind speed (m/s) at existing towers. Red circle shows location of tower referenced in the text. Wind speeds at tower sites are adjusted for 70 m AGL based upon the on-site vertical wind speed shear exponents).

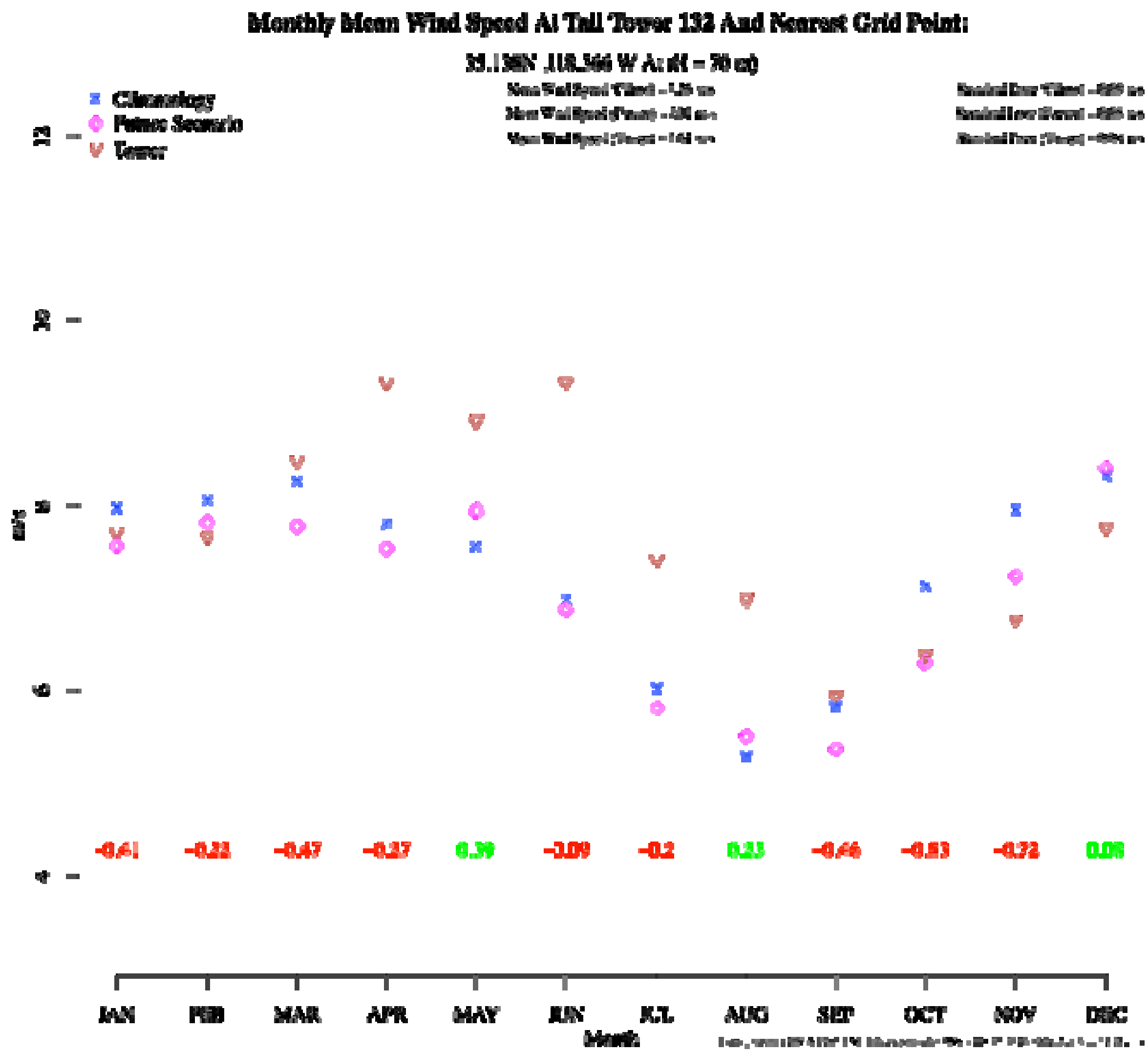

Figure A3: Monthly Distribution of 50 m Wind Speeds (m/s) at Tehachapi Pass.
(Blue x's are the historical climatology of the model, magenta diamonds are model future scenario, and brown triangles are six years of tall tower measurements. Red (green) numbers represent decrease (increase) in wind speed between the climatology and future scenarios.)

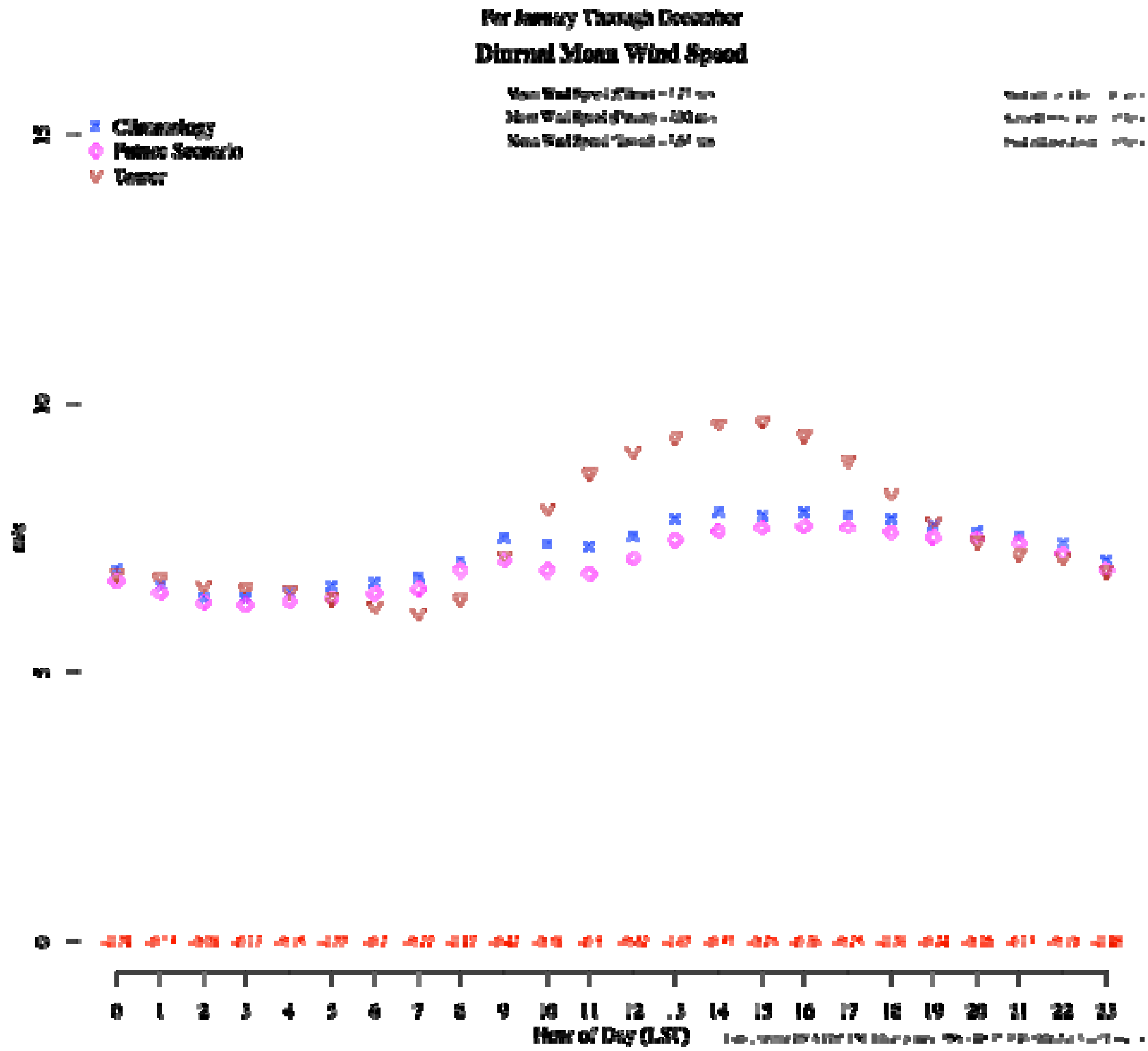

Figure A4: Diurnal Mean Wind Speed for Jan. – Dec.

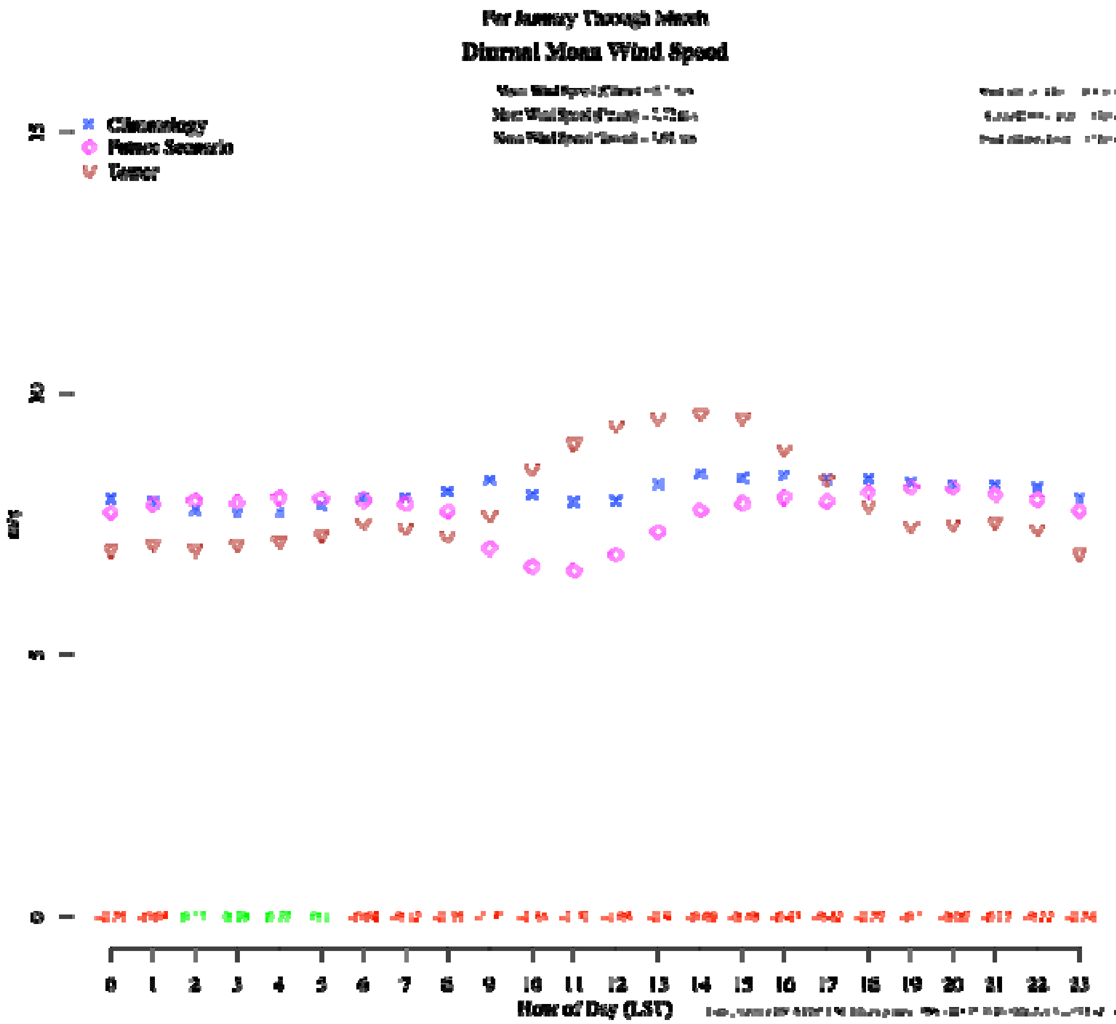

Figure A5: Diurnal Mean Wind Speed, Jan. – Mar.

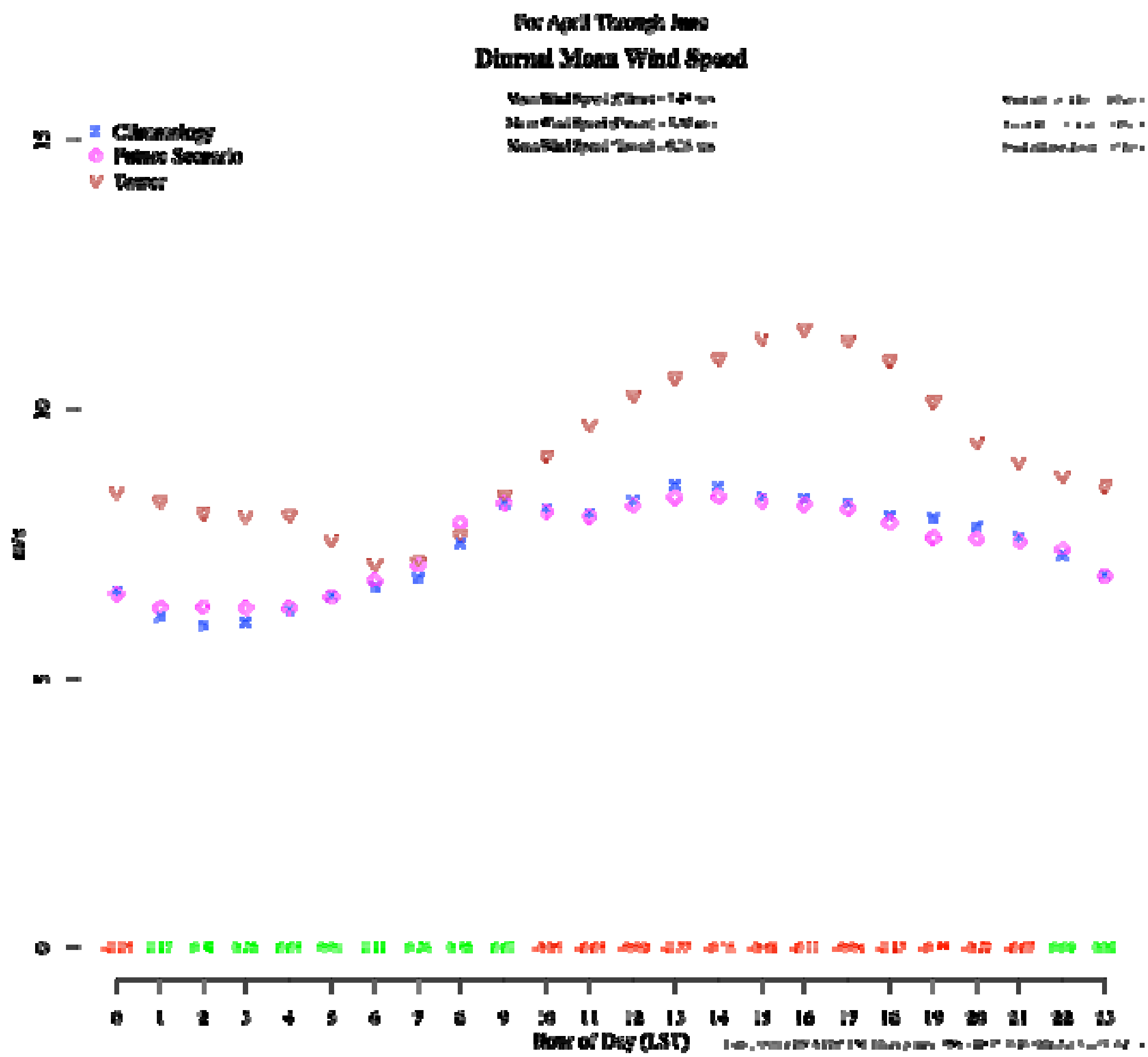

Figure A6: Diurnal Mean Wind Speed, Apr. – Jun.

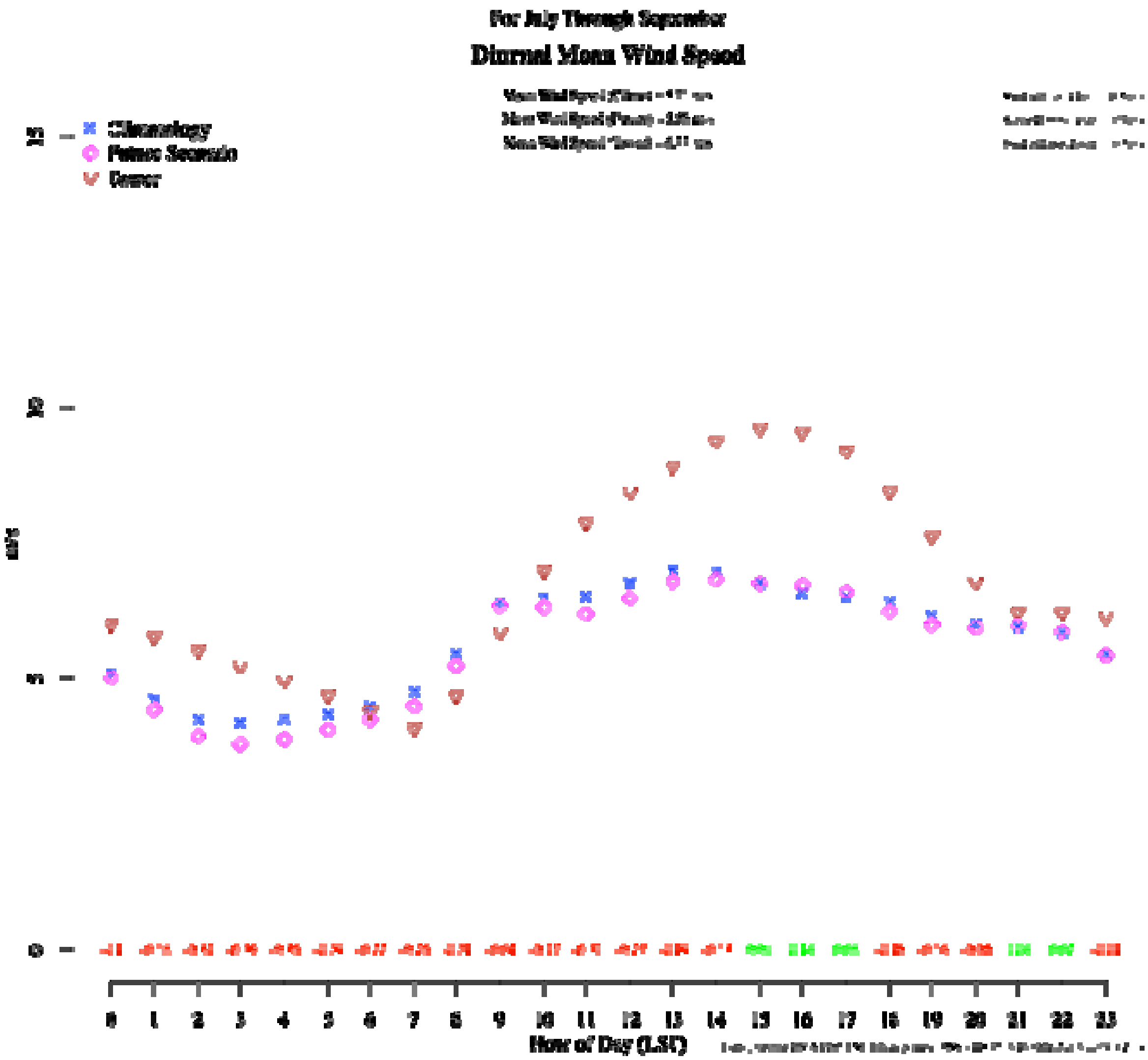

Figure A7: Diurnal Mean Wind Speed, Jul. – Sep.

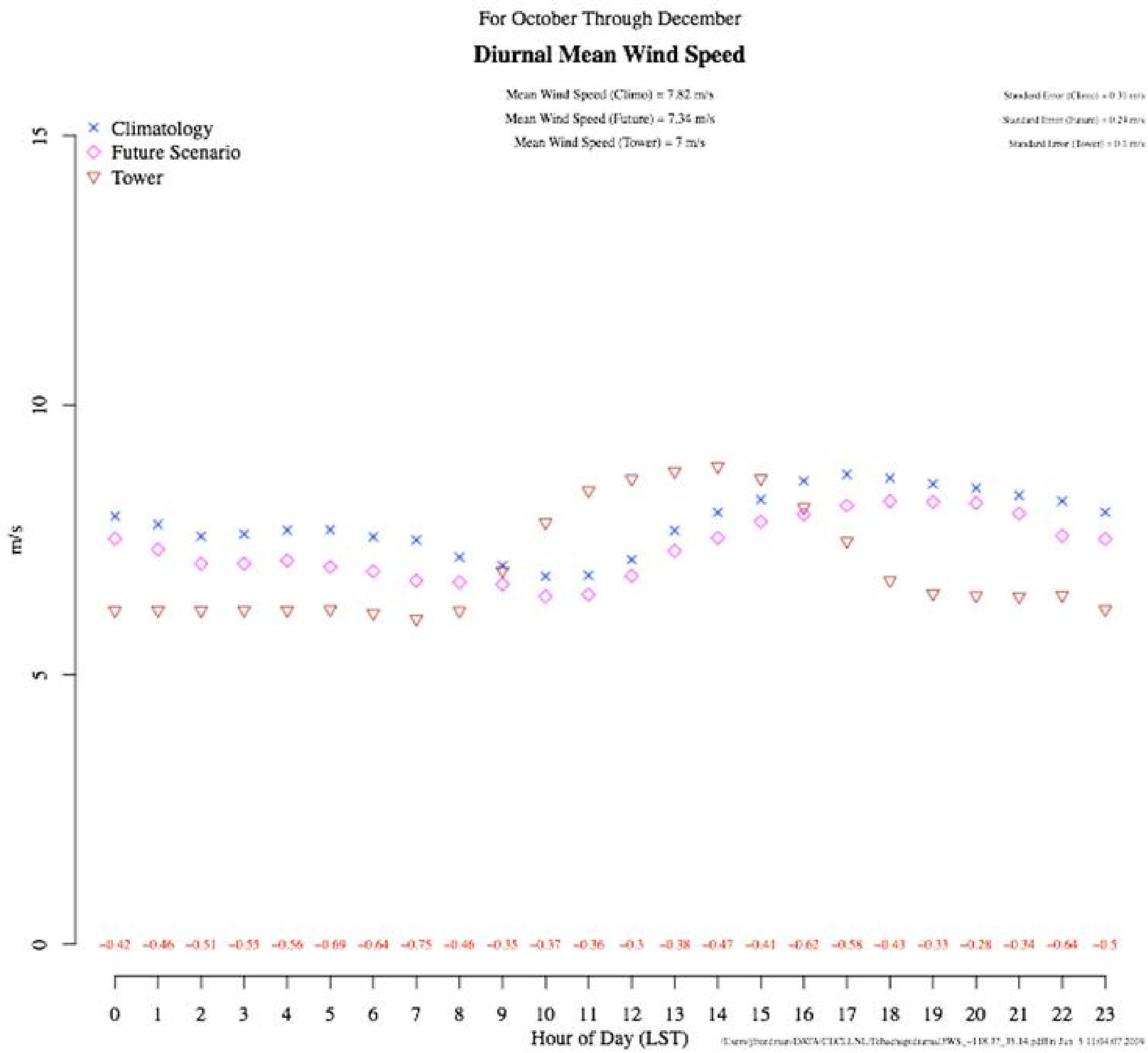

Figure A8: Diurnal Mean Wind Speed, Oct. – Dec.

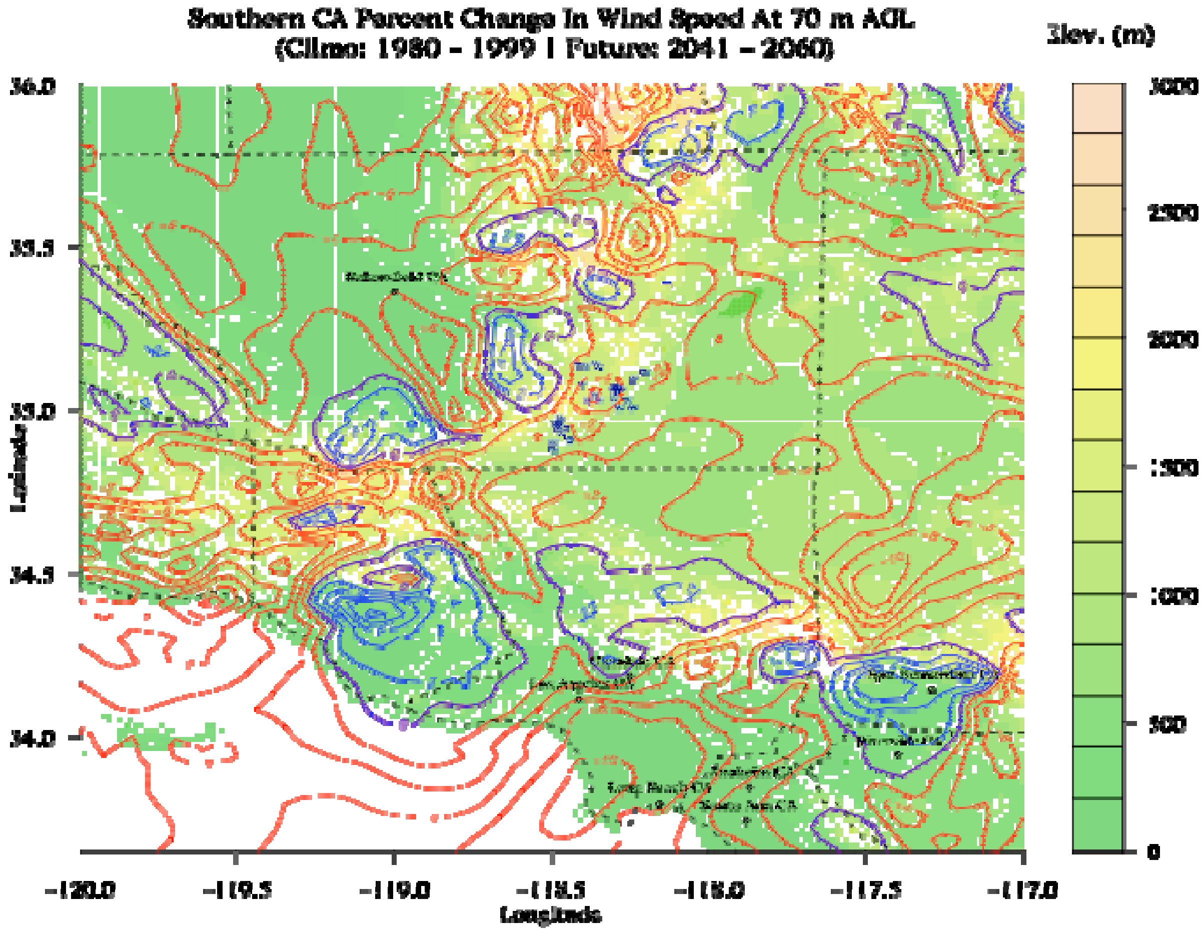

Figure A9: MASS 4-km Climatological Wind Speed Percentage Change Between Present (1980 - 1999) and Future Scenarios (2041–2060).

(W's represent locations of existing and proposed wind farms. Red contours represent a decrease in wind speeds, blue numbers a net increase).

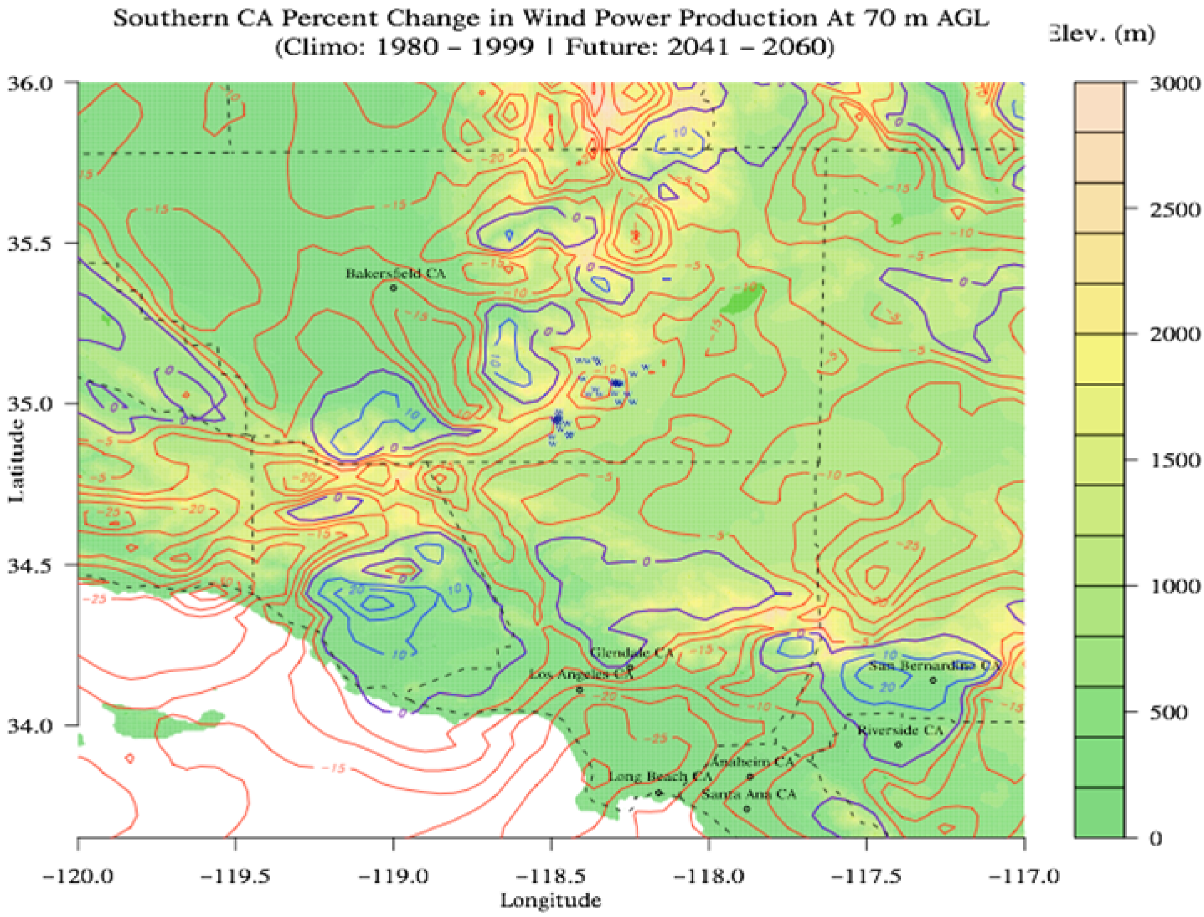

Figure A10: Percentage Change in Wind Power Production.

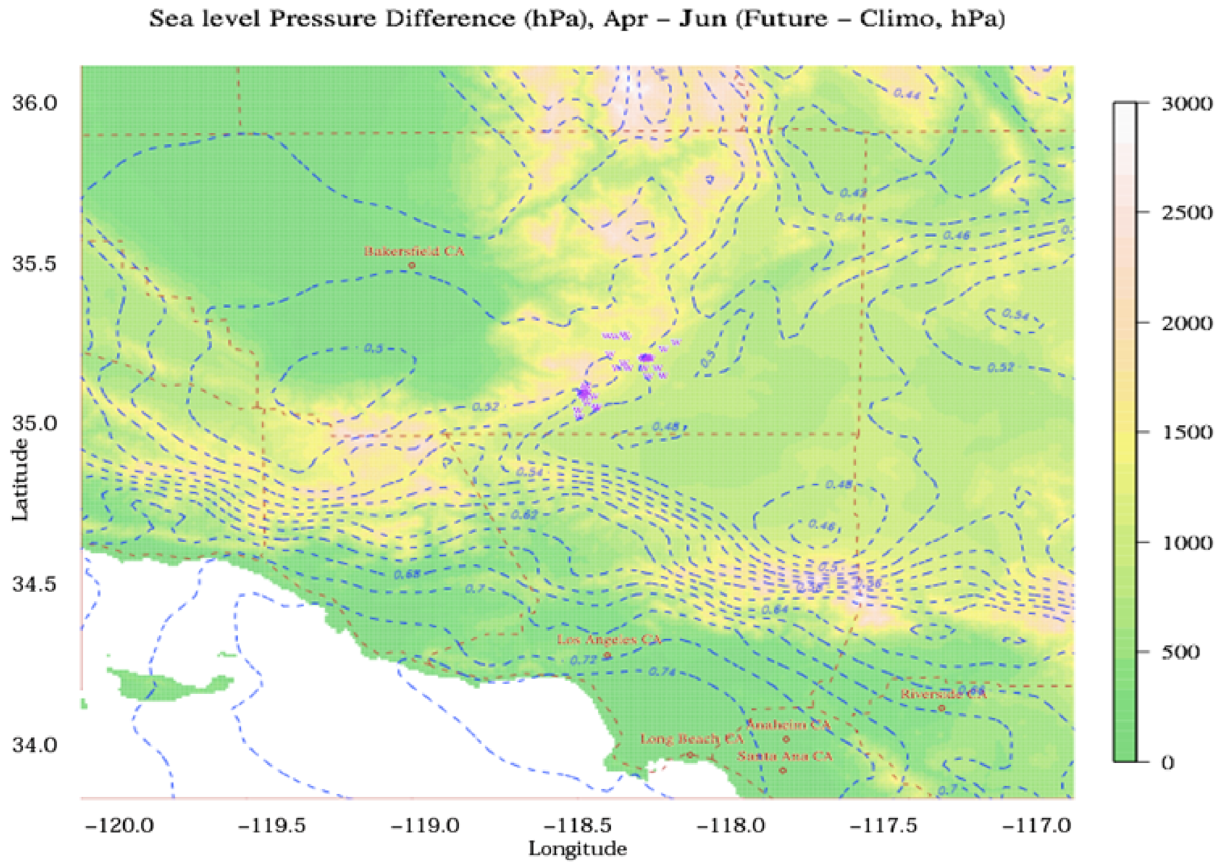

Figure A11: April – June Sea Level Pressure Change (hPa) for the Future-Climatology Scenarios.

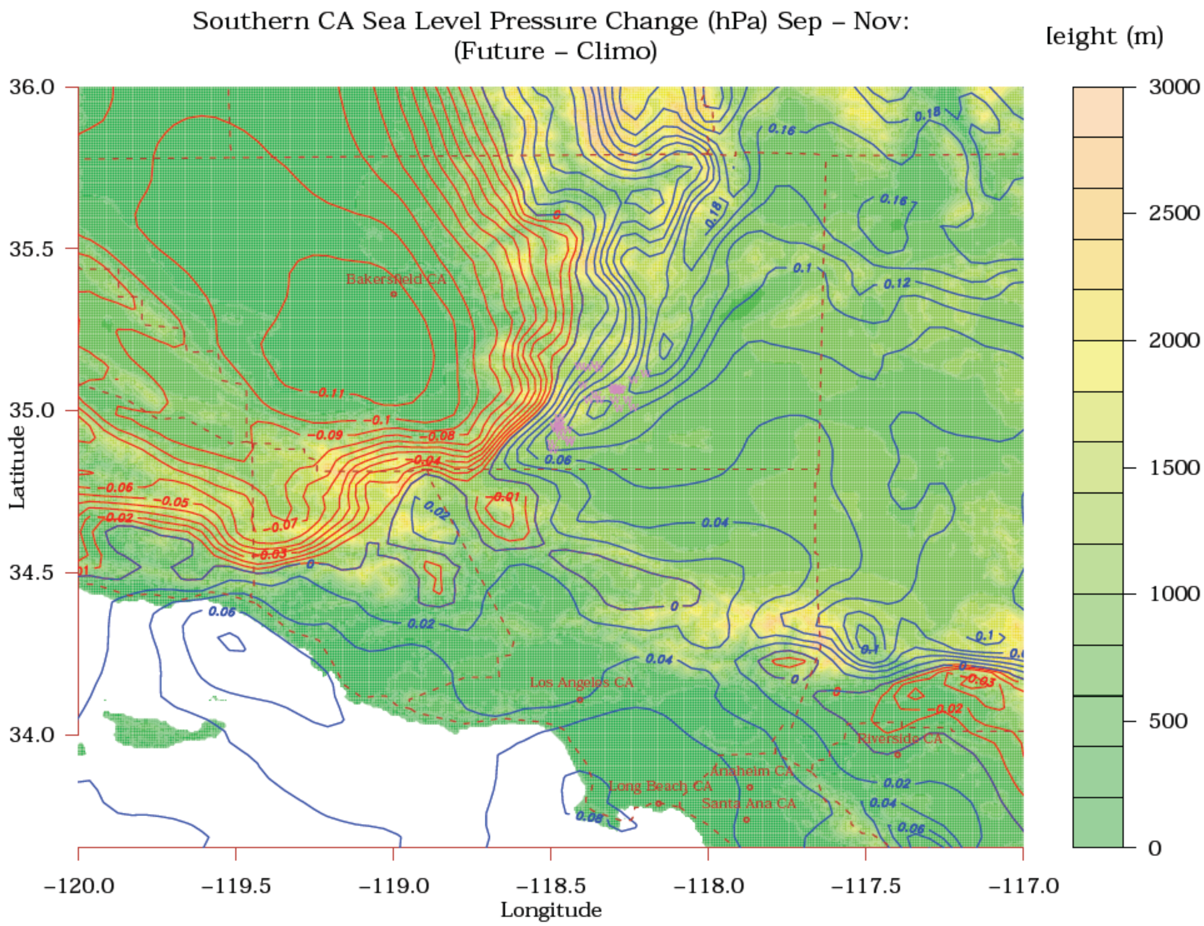

Figure A12: Sea Level Pressure Change (hPa) for the Future-Climatology Scenarios September–November.