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MODELED REGIONAL CLIMATE CHANGE IN THE HYDROLOGIC REGIONS OF CALIFORNIA: A CO_2 SENSITIVITY STUDY[1]

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ABSTRACT: Using a regional climate model (RegCM2.5), the potential impacts on the climate of California of increasing atmospheric CO_2 concentrations were explored from the perspective of the state's 10 hydrologic regions. Relative to preindustrial CO_2 conditions (280 ppm), doubled preindustrial CO_2 conditions (560 ppm) produced increased temperatures of up to 4°C on an annual average basis and of up to 5°C on a monthly basis. Temperature increases were greatest in the central and northern regions. On a monthly basis, the temperature response was greatest in February, March, and May for nearly all regions. Snow accumulation was significantly decreased in all months and regions, with the greatest reduction occurring in the Sacramento River region. Precipitation results indicate drier winters for all regions, with a large reduction in precipitation from December to April and a smaller decrease from May to November. The result is a wet season that is slightly reduced in length. Findings suggest that the total amount of water in the state will decrease, water needs will increase, and the timing of water availability will be greatly perturbed.

(KEY TERMS: climate change; modeling; meteorology/climatology; water resources planning; water demand; California; CO_2.)

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INTRODUCTION

The anthropogenic input of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2) is modifying global climate in measurable ways. Observations of global temperature show that annual average temperature rose by 0.6°C over the 20th century (Jones *et al.,* 2000). The period of 1990 to 2000 was the warmest decade of the past century, with the two warmest years ever recorded occurring in 1998 and 2000 (Jones *et al.,* 2000). The most recent report by the Intergovernmental Panel on Climate Change (IPCC; IPCC Working Group I, 2001) presents a growing body of scientific work that examines the causes and consequences of climate change. Results of the global climate model (GCM) from the report project that temperatures will rise on a global average basis by approximately 1°C to 5°C by 2100. The report predicts increased temperature in western North America by the end of the century, but the change in precipitation (either an increase or decrease) is uncertain. Estimates of changes in snow accumulation are not presented.

To date, the use of GCMs for projections of future climate change has been widespread (IPCC Working Group I, 2001). These studies have focused primarily on changes in climate at the global scale. While some work has considered regional climate change using GCMs (e.g., IPCC, 2001), a conclusion of this work is that GCMs lack the necessary resolution and physics to adequately address regional climate change. To provide a better estimate of the consequences of global warming on a regional scale, a regional climate model (RCM) was employed. Statistical downscaling of GCM data is another possible approach to this problem (Wilby *et al.,* 2000). The statistical method is dependent upon empirical relationships of climate variables. An advantage of the RCM over the statistical method is the use of physically based relationships among variables. This makes the RCM more consistent with the GCM, especially in this study, where the GCM and RCM use the same solar radiation package. A weakness of the statistical method is that as the

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climate system changes, due to increased greenhouse gas concentrations, the empirical relationships that statistical downscaling methods are dependent on may no longer hold true.

The work presented here utilizes a high resolution RCM (RegCM2.5), driven by GCM (CCM3) output, to evaluate the impacts of future climate change on the state of California. California is a region of complex topography that cannot be resolved by GCMs (Figure 1) and low resolution RCMs (i.e., more than 2,000 km^2 grid cell). Narrow mountain ranges such as the Coast Range that are 40 to 60 km in width with elevations of up to 1,450 m require models with resolutions comparable to the scale of these features in order to resolve the climate adequately. As Figure 1 demonstrates, even large scale topographic features like the Sierra Nevada Range and Cascade Range are not resolved in the GCM.

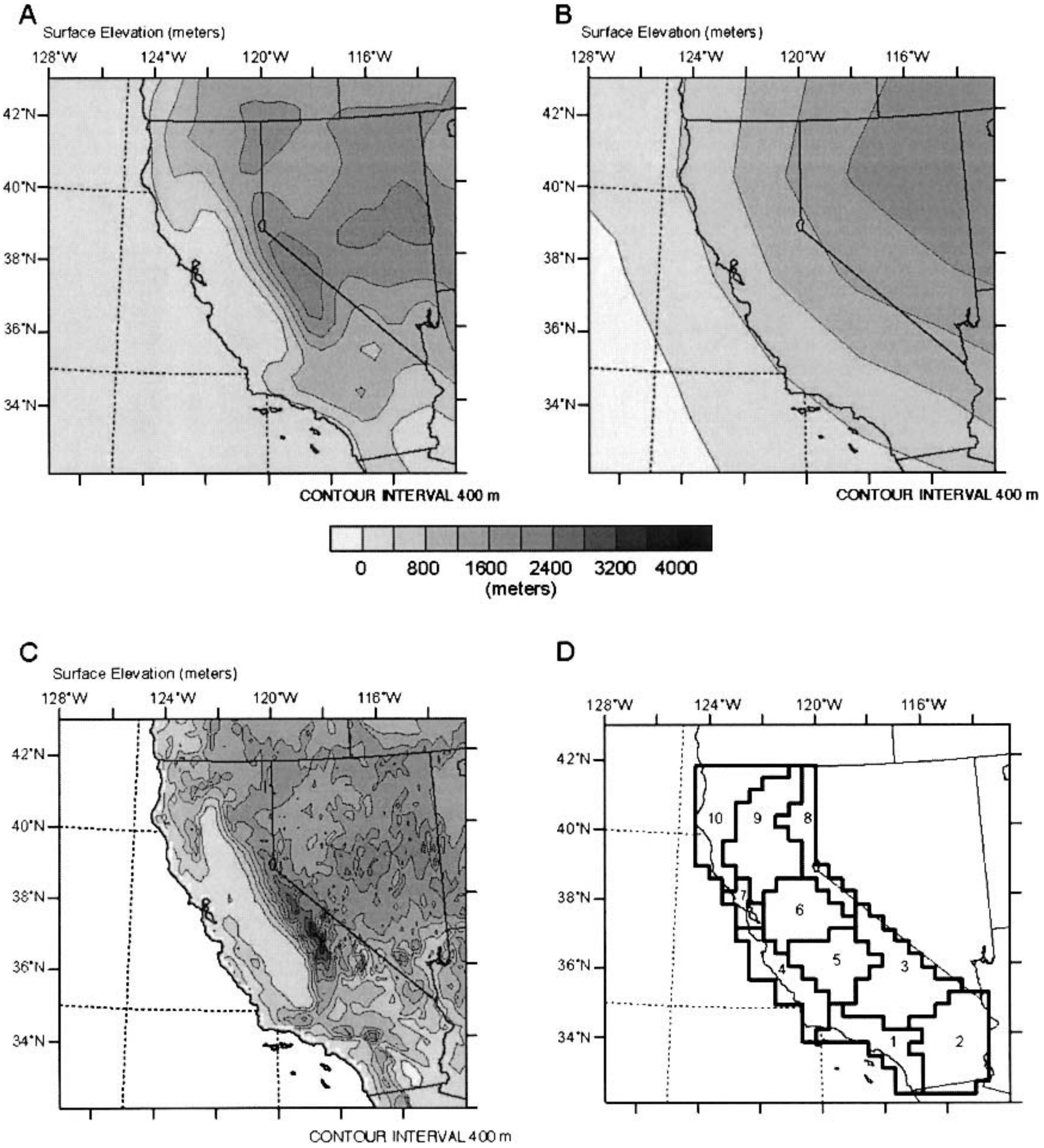

Figure 1. Topography of California and Map of the 10 Hydrologic Regions of California. (A) Topography of the regional climate model (RegCM2.5). (B) Topography of the global climate model (CCM3). (C) Ten-minute resolution topography of California. (D) The 10 hydrologic regions of California as defined in the regional climate model: (1) South Coast; (2) Colorado River; (3) South Lahontan; (4) Central Coast; (5) Tulare Lake; (6) San Joaquin; (7) San Francisco Bay; (8) North Lahontan; (9) Sacramento River; and (10) North Coast.

The scope of existing studies of the impacts of climate change on California is limited to a fraction of the state's area (Stamm and Gettelman, 1995; Kim, 2001; Knowles and Cayan, 2002) or focus more broadly on regional change in the western United States (Giorgi *et al.,* 1994; Thompson *et al.,* 1998; Kim *et al.,* 2002). One study to date that has focused on the possible future climate of California in its entirety is Snyder *et al.* (2002). Previous regional climate modeling studies of future climate change in California have suggested increased temperature, with the greatest warming at high elevations (Kim, 2001; Snyder *et al.,* 2002). While Kim (2001) looked at monthly responses for temperature, precipitation, and snow, he focused on three small mountain regions. In contrast, Snyder *et al.* (2002) examined the results for the entire state. Kim (2001), using 10 years of model integration and with driving data from a transient GCM run, showed increased precipitation in mountain regions, while Snyder *et al.* (2002), employing three ensembles of five-year model integrations, showed increased precipitation in the northern portion of the state and decreases or no change in the rest of the state. Results from both studies show significantly decreased snow accumulation under increased CO_2 conditions.

This study builds on that of Snyder *et al.* (2002) and presents the likely changes in future climate due to increased greenhouse gas forcing for the 10 hydrologic regions encompassing California, as defined by the state Department of Water Resources (CDWR, 1998) (Figure 1). These results are based on 15 years of model integration in each case. By examining results in this framework, the authors hope to provide information to individuals and institutions that are interested in assessing the impacts of climate change in particular regions (e.g., water districts).

METHODS AND MODELS:

A modified version of the RegCM2 RCM (Giorgi *et al.,* 1997; Giorgi and Shields, 1999; Small *et al.,* 1999; Sun *et al.,* 1999; Jenkins and Barron, 2000; Kato *et al.,* 2001) was used for this study, hereafter referred to as RegCM2.5. RegCM2.5 contains the radiation package of the Community Climate Model, version 3.6.6 (CCM3), which is an improvement over the previous version of RegCM. RegCM2.5 is a hydrostatic limited area model coupled to a land surface model. The land surface model is BATS (version 1e) (Dickinson *et al.,* 1993). For this study the horizontal resolution of the model was 40 km, with 60 grid cells in the north/south direction and 55 grid cells in the east/west direction. The vertical resolution was set at 14 levels.

The CCM3 (Version 3.6.6) (Kiehl *et al.,* 1998) was used to produce the boundary conditions for the RCM. This model was configured with a horizontal resolution of 2.8 degrees latitude by 2.8 degrees longitude. The model has 18 vertical levels. First, a version of the model with a slab ocean thermodynamic sea ice model was used. Two 18-year simulations were performed to generate the boundary conditions for the RCM. These differed only in the specified concentrations of CO_2, which was 280 ppm (preindustrial value) in one case and 560 ppm in the other. These scenarios are hereinafter referred to as the 1X and 2X cases, respectively. All other boundary conditions were set to present values. Because model output was saved at monthly frequency, the resulting sea surface temperatures (SSTs) were used in a second pair of CCM3 experiments with corresponding levels of atmospheric CO_2. Results from these cases were saved at 12-hour frequencies for input to RegCM2.5. In this study, the GCM runs that were used in Snyder *et al.* (2002) were extended out to 21 years. The RCM runs in this study are extensions of two ensemble members from Snyder *et al.* (2002) – one $1xCO_2$ run and one $2xCO_2$ run. The RCM runs were extended out to 18 years, with the last 15 years of data used in the analyses presented here. Since this study was constructed in a sensitivity study format, the important result is the response of climate to the doubling of atmospheric CO_2 concentration (pCO_2).

The RCM has been validated against observations of modern day climate. It was found that the model compares well to data from seven stations distributed throughout the state for temperature, precipitation, and where available, snow accumulation (Snyder *et al.,* 2002). A more recent validation for a larger number of observational stations finds that the RCM does well for temperature and precipitation (Bell *et al.,* 2004). Based on a comparison of 16 observational stations across California, Bell *et al.* (2004) finds that for temperature the RCM has a bias of 1.4°C for December through February (DJF); 2.4°C for March through May (MAM); -0.4°C for June through August (JJA); and -0.5°C for September through November (SON). The RCM precipitation biases are -5.0 cm for DJF; -2.7 cm for MAM; 1.7 for JJA; and 0.5 cm for SON. These results are good considering that the model results are at 40 km horizontal resolution and are being compared directly to observational stations.

A comparison of the GCM output to observations, to see how well the GCM does in simulating modern climate compared to the RCM, was also done in Bell *et al.* (2004). For the same 16 observational stations, the RCM was closer to observations than the GCM for

75 percent of the 540 individual observations that were used in the evaluation.

RESULTS

The output from the RCM was subdivided into the 10 hydrologic regions as defined by the CDWR (1998; see Figure 1). The hydrologic regions vary in area and generally cover unique climatic areas. Results were analyzed on a monthly and annual basis for temperature, precipitation, and snow accumulation. Changes in the median of each variable are presented here, focussing on a comparison of results for the 1X case and the 2X case. Values are reported in terms of the median instead of the mean because the median provides better representation of variables such as precipitation and snow accumulation whose distributions tend to be skewed from a normal (Gaussian) distribution. Using the mean to evaluate the data masks the true nature of their distribution. Although temperature generally has a symmetric distribution, the median is used for consistency.

CHANGES ON AN ANNUAL BASIS

For all hydrologic regions, the median annual temperature increases in the range of 1.9°C to 4.0°C (Table 1) (2X results versus 1X results). Temperature changes are statistically significant at the 95 percent confidence interval in all regions (Table 1). The greatest increase is in the Sacramento River region, and the smallest increase is in the Tulare Lake region. Median annual precipitation (Table 1) indicates reductions in the 2X case for the six southernmost regions (-7.2 to -17.1 percent), while the four northernmost regions show minor increases (0.5 to 7.1 percent). The changes in precipitation are not statistically significant in any region. The decreases in precipitation are greatest in the southernmost regions, and the amount of decrease is reduced moving to the north up to the San Francisco Bay region. The three northernmost regions show slight increases in annual precipitation.

Annual snow accumulation decreases in the 2X case relative to the 1X case for all hydrologic regions (Table 1). The changes in snow accumulation are statistically significant at the 95 percent confidence interval in the Tulare Lake, San Joaquin River, North Lahontan, Sacramento River, and North Coast regions (Table 1). Decreases in snow accumulation, by volume, are greatest in the Sacramento River, the North Coast, and the San Joaquin River regions.

CHANGES ON A MONTHLY BASIS

Temperature

The results show an increase in temperature for each of the 10 regions on a monthly basis (Table 2, Figure 2) in response to a doubling of pCO_2. The temperature changes on a monthly basis are statistically significant at the 95 percent confidence interval in all months and all regions except the four northernmost regions in December (Table 2). The amount of warming is greatest in February, March, and May, followed by April and August, while the warming for the remaining months is less. The net result is milder winter temperatures, an earlier arrival of spring, and increased summer temperatures. Median monthly temperatures increase by up to 5°C (in the North Lahontan region in February). The only decrease in monthly temperature is by 0.17°C in the North Lahontan region in December, although this change is not statistically significant. For most regions, the temperature increase is greater than 2°C in every month of the year (Table 2).

TABLE 1. Changes by Regions: 2X Case Minus 1X Case – Annual Average (temperature in °C, precipitation percent change, and snow accumulation as percent change).

	1	2	3	4	5	6	7	8	9	10
Median Temperature	**2.5**	**2.1**	**2.2**	**2.3**	**1.9**	**3.0**	**2.0**	**2.3**	**4.0**	**3.2**
Median Precipitation	-17.1	-11.8	-10.3	-12.3	-7.2	-4.3	3.1	7.1	0.5	3.4
Snow Accumulation	-89.5	-85.7	-57.0	-94.1	**-59.2**	**-49.0**	-91.6	**-34.5**	**-61.8**	**-73.1**

Note: The values highlighted in bold are significant at the 95 percent confidence interval based on a paired t-test. Regions are as follows: (1) South Coast, (2) Colorado River, (3) South Lahontan, (4) Central Coast, (5) Tulare Lake, (6) San Joaquin River, (7) SF Bay, (8) North Lahontan, (9) Sacramento River, (10) North Coast.

Table 2. Monthly Median Temperature Difference (°C): 2X Minus 1X Case.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
January	**1.50**	**1.49**	**2.25**	**1.64**	**2.37**	**1.98**	**1.77**	**3.75**	**2.88**	**3.03**
February	**3.98**	**2.90**	**4.65**	**3.26**	**4.07**	**3.75**	**2.33**	**4.96**	**3.05**	**3.81**
March	**3.76**	**3.11**	**3.89**	**3.55**	**4.35**	**3.74**	**2.77**	**3.97**	**3.45**	**3.05**
April	**3.30**	**2.99**	**2.90**	**2.42**	**2.93**	**1.96**	**1.21**	**3.18**	**2.81**	**2.15**
May	**3.06**	**3.28**	**3.30**	**2.68**	**3.27**	**3.93**	**2.22**	**3.77**	**4.45**	**3.43**
June	**2.07**	**2.50**	**2.99**	**2.39**	**3.14**	**3.40**	**2.13**	**3.69**	**2.97**	**2.13**
July	**2.27**	**1.80**	**3.12**	**1.71**	**2.64**	**2.73**	**2.00**	**3.34**	**2.76**	**2.91**
August	**2.36**	**3.21**	**3.93**	**2.02**	**3.46**	**2.73**	**1.88**	**2.96**	**2.53**	**2.76**
September	**2.76**	**2.90**	**2.84**	**2.55**	**2.96**	**2.68**	**2.45**	**2.55**	**2.61**	**2.57**
October	**1.54**	**1.92**	**1.41**	**1.60**	**1.27**	**1.30**	**2.26**	**1.01**	**1.31**	**1.54**
November	**1.42**	**1.33**	**1.26**	**0.85**	**1.24**	**1.15**	**0.97**	**1.23**	**1.07**	**1.03**
December	**1.32**	**1.46**	**2.11**	**0.86**	**1.29**	**1.23**	0.83	-0.17	1.94	1.10

Note: The values highlighted in bold are significant at the 95 percent confidence interval based on a paired t-test. Regions are the same as in Table 1.

Precipitation

Precipitation responses to a CO_2 doubling show generally drier conditions for all regions in most months of the year that receive significant precipitation (Table 3, Figure 3). The monthly precipitation changes are not statistically significant for any region in any month (Table 3). Most regions exhibit a large reduction in precipitation in the period of February and March and for the months of October and December. The four southernmost regions (South Coast, Colorado River, South Lahontan, and Central Coast regions) show slightly wetter Januarys in the 2X case, and the five northern regions show slightly more precipitation in April. All regions except the North Coast region have slightly more precipitation in November in the 2X case. Late spring, summer, and early autumn, typically dry periods for California, show no change in the amount of precipitation for all regions.

Snow Accumulation

For all relevant regions of the state there is a substantial decrease in the amount of snow accumulation in each month (Table 4, Figure 4). Changes in monthly snow accumulation are statistically significant at the 95 percent confidence interval in the mountainous regions from January through May (Table 4). In most of the regions in the 2X case, almost all snow accumulation ceases a month earlier relative to the 1X case. This implies an earlier start to the spring runoff by approximately one month. The first snow accumulation of the year still occurs in November, but the amount of snow accumulation decreases dramatically for all months.

DISCUSSION

The results presented here demonstrate the sensitivity of the RegCM2.5 RCM, as driven by the CCM3 GCM, to a change in the concentration of CO_2 in the atmosphere from 280 ppm to 560 ppm. This change in concentration approximately corresponds to the difference between conditions of the late 1800s and of 2050. These results provide important insights into the effects of changing atmospheric CO_2 concentration on the spatial and temporal aspects of the climate of California.

Changes in temperature are driven primarily by an increase in the absorption of shortwave radiation at the surface. Areas with the greatest increase in surface temperature (i.e., the high elevations of the Cascades and the Sierra Nevada) correspond with areas of largest increased solar flux at the surface. The increased solar flux at the surface is due to a decrease in clouds, which allows more radiation to reach the surface. The decrease in clouds over some regions is caused by shifts in the large scale atmospheric circulation. The increased surface temperature leads to less snow accumulation in the winter, which in turn decreases the surface albedo, leading to the absorption of more radiation. Thus a positive feedback is created in which the absorption of more radiation leads to warmer temperatures, thereby decreasing snow accumulation and albedo further.

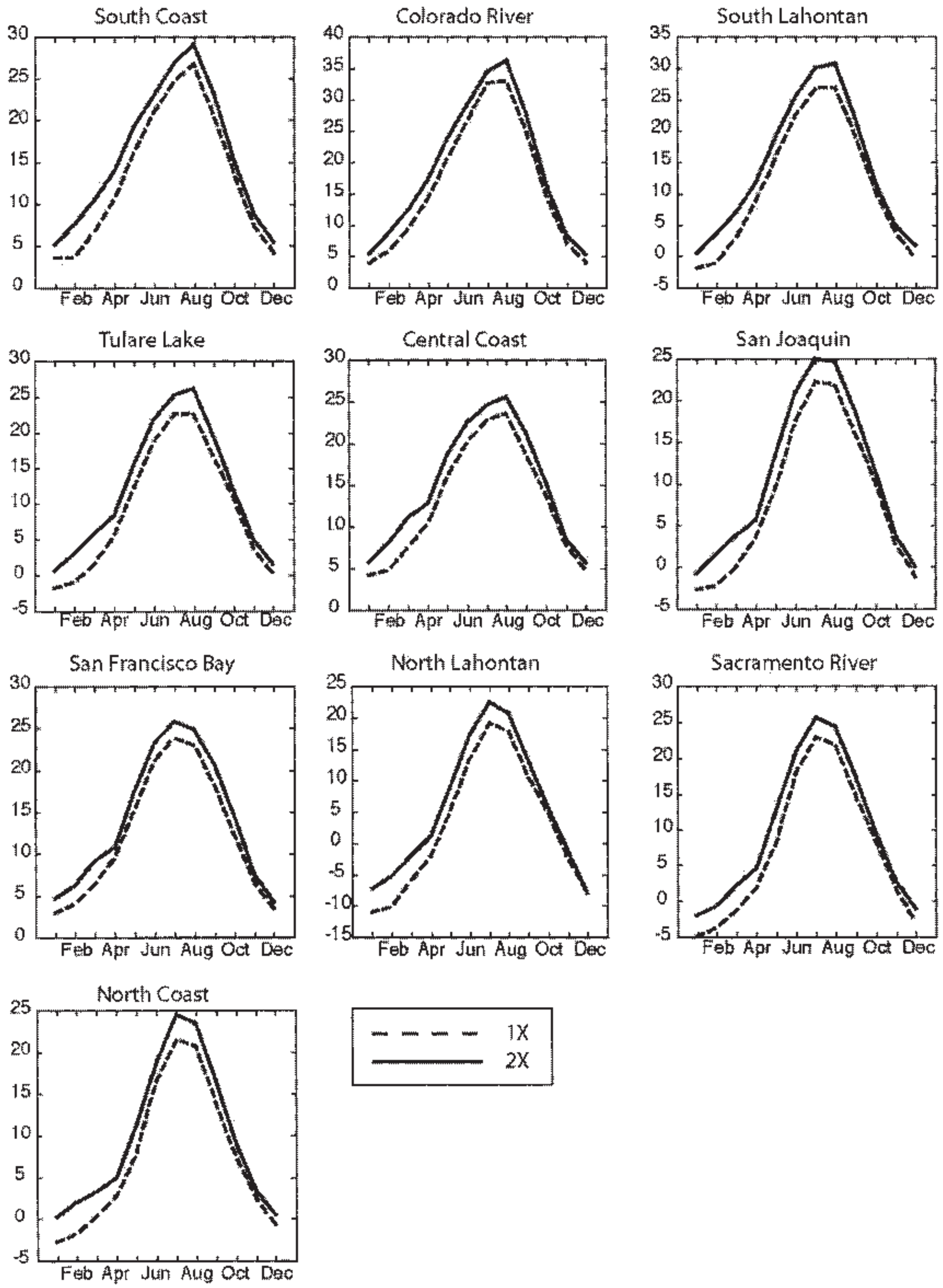

Figure 2. 1X and 2X Monthly Surface Temperature (Celsius) by Region.

TABLE 3. Monthly Median Precipitation Difference (mm/day): 2X Minus 1X Case.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
January	0.649	0.205	0.177	0.068	-0.069	-0.731	-0.128	-0.117	-0.130	0.080
February	-0.044	-0.045	-0.028	0.247	-0.299	-1.317	-0.761	0.119	-3.009	-2.929
March	-0.646	-0.286	-0.201	-1.512	-0.884	-2.704	-1.791	-0.307	-2.189	-0.912
April	-0.241	-0.052	-0.095	-0.338	-0.380	0.056	0.432	0.168	0.170	1.738
May	0.022	0.000	-0.013	0.026	0.285	0.065	0.154	0.213	0.182	0.010
June	0.001	0.000	0.007	-0.007	-0.092	-0.087	-0.005	-0.243	-0.162	-0.047
July	-0.012	0.000	0.002	0.000	0.017	0.003	0.000	0.004	0.002	-0.033
August	0.023	-0.001	0.022	0.016	0.041	0.013	0.000	0.010	0.000	-0.002
September	0.034	-0.012	0.029	0.001	0.012	-0.001	0.000	-0.08	-0.005	-0.064
October	-0.003	0.000	-0.009	-0.007	0.000	0.032	-0.017	-0.017	-0.089	-0.344
November	0.208	0.127	0.102	0.144	0.345	0.126	0.542	0.129	0.344	-0.284
December	-0.507	-0.133	-0.187	-1.062	-2.045	-3.217	-0.555	-0.598	-2.615	-1.144

Note: The values highlighted in bold are significant at the 95 percent confidence interval based on a paired t-test. Regions are the same as in Table 1.

Precipitation changes are driven by the same slight changes in the location of Pacific pressure centers and the corresponding changes in atmospheric circulation driving storms across California. A shift in wintertime storm tracks to the north results in less moisture being delivered to California in the 2X case. Stronger high pressure over the western United States in the 2X case in the wintertime also accounts for some of the decreases in precipitation and snow accumulation. This higher pressure tends to deflect wintertime storms away from California.

In examining the mean monthly temperature changes between model cases for all 10 basins, the North Lahontan region stands out because this region has the largest temperature change for the greatest number of months (the largest monthly temperature increases in four months, and the second-largest increase in two months; Table 2).The nature of this response is due to the location of the region. The North Lahontan region includes high latitude, inland, and high-elevation locations (Figure 1). As shown in this and other work (e.g., Giorgi *et al.,* 1997; Meehl *et al.,* 2000; Snyder *et al.,* 2002), temperature response to increased atmospheric greenhouse gases is typically greater for higher latitude regions than lower latitude regions, typically greater for inland versus coastal regions, and greater at higher elevations than lower elevations (with all other factors being equal). All three of these factors combine to produce the greatest response to increased pCO_2 in the North Lahontan region. A similar, although lesser, response is seen in the other high elevation inland regions (Colorado River and South Lahontan). The South Lahontan region has the largest temperature increase in two months and the second largest in two months. The Colorado River region has the second largest increase in four of the months. Overall these three regions account for six of the months with the most warming and eight of the months with the next greatest warming.

Previous work on the impacts of temperature change has shown a wide range of possible impacts. For example, an increase in maximum temperatures is expected to increase the demand for environmental cooling, and temperature increases are also predicted to reduce energy supply reliability (Colombo *et al.,* 1999). Higher temperatures will also cause shifts in the ranges of both plants and animals. Observational evidence has shown that the Edith's Checkerspot butterfly has shifted its range to the north and to higher elevations (Parmesan, 1996), likely in response to increasing temperature. Temperature increases on the order of 5°C will severely impact these and other temperature-sensitive organisms. At higher elevations, where the results show the greatest warming, some species will be unable to migrate to a suitable habitat. Plants are especially vulnerable, given their limited ability to disperse as a function of time.

Likewise, changes in precipitation and snow accumulation will impact both human and natural systems. Previous studies using global models show that significant impacts are likely to occur to hydropower, flooding, and water availability (Lettenmaier *et al.,* 1999; Blake *et al.,* 2000; Cohen *et al.,* 2000). Reductions in snow accumulation, due to temperature increase, will decrease the natural storage of water in the mountains for release during the spring and summer. More runoff will occur in the winter due to rain falling instead of snow during winter months. A limited amount of reservoir space is available for both

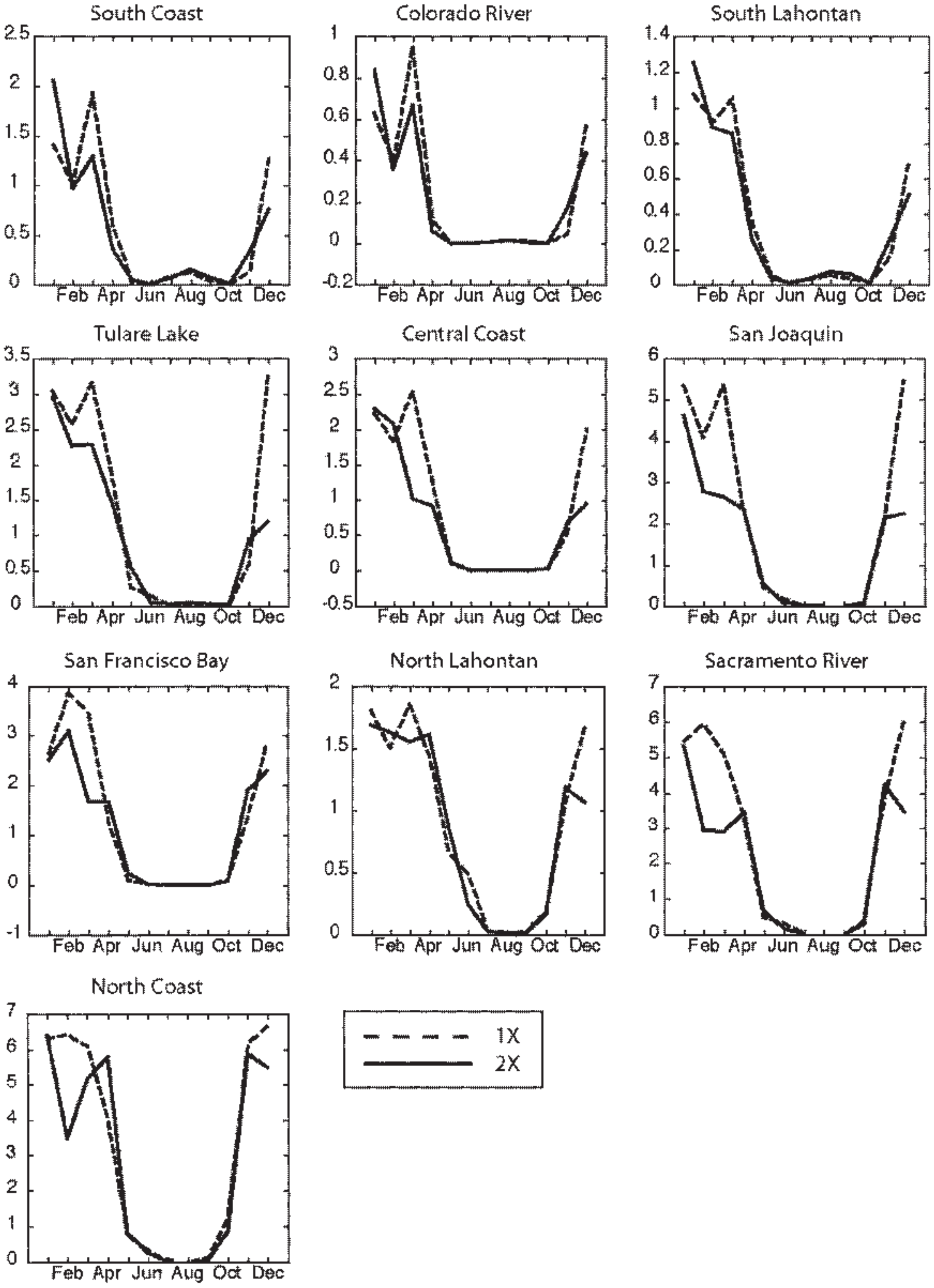

Figure 3. 1X and 2X Median Monthly Precipitation (mm/day) by Region.

TABLE 4. Monthly Median Snow Height Difference (mm snow water equivalent): 2Xminus 1X case.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
January	0.0	-0.1	-4.4	NA	**-23.7**	**-72.8**	NA	**-19.7**	**-55.0**	**-45.7**
February	-0.1	-0.1	**-2.8**	NA	**-37.1**	**-88.6**	NA	**-35.3**	**-99.1**	**-68.6**
March	NA	NA	**-1.2**	NA	**-45.2**	**-109.0**	NA	**-60.6**	**-171.8**	**-110.6**
April	NA	NA	**-0.1**	NA	**-37.7**	**-97.9**	NA	**-48.6**	**-125.5**	**-86.8**
May	NA	NA	NA	NA	**-5.7**	**-51.4**	NA	**-3.7**	**-23.2**	**-19.3**
June	NA	NA	NA	NA	NA	-1.1	NA	NA	NA	NA
July	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
August	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
September	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
October	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
November	NA	NA	NA	NA	0.2	-0.2	NA	-0.4	-2.4	**-2.8**
December	NA	NA	NA	NA	-2.0	-16.0	NA	6.6	-8.1	-6.6

Note: The values highlighted in bold are significant at the 95 percent confidence interval based on a paired t-test. NA indicates months and regions where no measurable snow accumulation occurs in either case. Regions are the same as in Table 1.

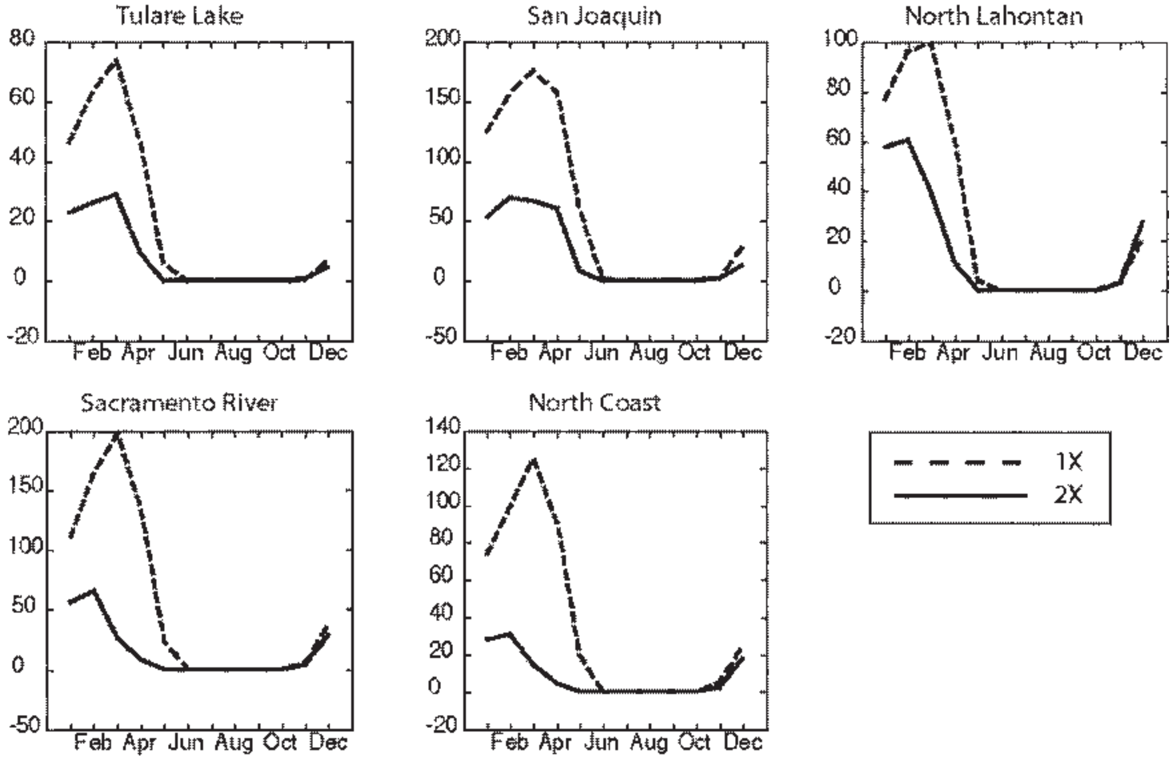

Figure 4. 1X and 2X Median Monthly Snow Accumulation (mm snow water equivalent) by Region.

water storage and flood control (Lettenmaier *et al.,* 1999). Reservoirs by necessity are kept at lower levels during winter months to prevent catastrophic flooding events. If more runoff occurs in the winter, reservoirs will be forced to release that water instead of storing it. As a result, during the spring and summer when reservoirs can begin storing water, there will be significantly less runoff with a reduced snow pack. With little increase in precipitation during the summer months to offset this loss, California can expect a significant reduction in usable water supply. The diminished runoff and reservoir levels will result in reduced reliability of hydroelectric power generation (Lettenmaier *et al.,* 1999). Adaptation to these changes would require significant modification of current water management practices to account for changes in the timing and the amount of runoff.

Natural systems will also suffer from these changes in runoff. Plants and animals that rely on runoff from snowmelt will find that streams and rivers will have dried up much earlier than before, and temperatures of the water are likely to increase, due to a reduction in snowmelt contribution. Competition with human consumption will become more intense, and it is likely that fish and other riverine taxa will be severely impacted. Adaptation to these changes will be crucial, making it important to assess the vulnerability of both humans and natural systems to changes in the water supply.

California's population is estimated to double by the year 2030 (U.S. Census Monitoring Board, 2000), and increased population will mean increased demand for energy and water resources. Coupled with increased temperatures, decreased precipitation, and decreased snow accumulation, the state is likely to face serious shortages of both water and electricity.

CONCLUSIONS

The results contained herein indicate that a doubling of atmospheric CO_2 concentrations from preindustrial values will lead to increased temperatures, decreased precipitation, and decreased snow accumulation. These results, from a high resolution RCM covering the entire state of California and focusing on the 10 hydrologic regions of the state, provide a comprehensive picture of future climate in California from a regional perspective. According to these results, high elevation regions will be most severely impacted by temperature and moisture responses.

On an annual basis, the results contained herein show slightly increased precipitation in the northern half of the state, while the southern half shows decreases in the amount of precipitation. Temperature results from the RCM indicate increases statewide by up to 4°C. These results also show that snow accumulation decreases significantly in all parts of the state.

Monthly changes in temperature are very similar for all regions of the state except the North Lahontan region in December. In all regions, excluding the North Lahontan region in December, the RCM results show increased temperature for all months of the year, with the greatest increases occurring in the spring months. Precipitation responses from the RCM are variable for all of the regions, with winter months showing generally decreased precipitation. Monthly snow accumulation from the RCM shows significant decreases for all the regions and all months. Given this information, it is likely that California's water supplies and water storage and delivery systems will be greatly perturbed by these changes.

The RCM results suggest that California will be strongly impacted by climate change. Increased temperatures may affect agricultural production, energy consumption, water consumption, human health, and ecosystems. Changes in precipitation and decreased snow accumulation may affect water storage and delivery, causing greater stress on a system already under significant pressure. Adaptation to these changes will likely necessitate significant changes in current water management practices.

In the future the authors would like to further examine the relationship between elevation and changing climate, especially for California and other topographically complex regions. As was discussed earlier, the results indicate that the higher elevations tend to warm more rapidly than lower elevations. The snow albedo feedback seems to play a large role in these temperature changes. Future work will also examine the effects of using different GCM boundary conditions to force the RCM.

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