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# Future regional climate change in the ten hydrologic regions of California: A climate modeling investigation

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# Future regional climate change in the ten hydrologic regions of California: A climate modeling investigation

## Abstract

This study will focus on two questions: (1) how will anthropogenically driven climate change affect California's climate, especially the hydrologic resources, in the coming decades?; and (2) what water resources will be available in the future, and at what times during the year (e.g., seasonality and amounts of rain and snow)? We apply global and regional climate models to a domain centered upon California to answer these questions. We will use a 40-km (gridpoint) resolution regional climate model (RCM) in order to capture the topographic complexity of the state, and the climate associated with that complexity. This model has been demonstrated to represent well the observed present climate of California. We will specify atmospheric greenhouse gas concentrations as predicted by the Intergovernmental Panel on Climate Change (IPCC) for the next several decades, and calculate the climate that would likely occur under these conditions, as compared to modeled scenarios of present day climate. From this project we will produce climate model results of future climate scenarios. Climate model results (and the statistical significance of the results) for annual and monthly periods of time will be calculated for the ten hydrologic regions of California as defined by the California Department of Water Resources. The quantitative results from this work will be made available for water policy and planning activities in the state, and for archival at the UC Center for Water Resources.

## Introduction and Problem Statement

It has been conclusively demonstrated that atmospheric greenhouse gas (GHG) concentrations are increasing at unprecedented rates (*Keeling and Whorf*, 2000). Observations also demonstrate an increase in global mean temperature (*IPCC*, 2001; *Jones et al.,* 2000; *Bradley*, 2000) and suggest the occurrence of increasingly extreme climate events (*Easterling et al*., 2000) as a result of GHG increases. Based upon projected rates of GHG increases and upon global climate modeling scenarios, the most recent Intergovernmental Panel on Climate Change (IPCC) report estimated a 5.8°C rise in global mean temperature over the next century (*IPCC*, 2001). Such estimates of global warming are large, and yet, the regional responses could be even larger, because regional responses to increasing GHG concentrations are much more variable than the mean global response. Importantly, the regional climate responses to increased GHG concentrations are much harder to predict, and have not been investigated as thoroughly as have global responses to date. While the U.S. National Assessment report examined the potential consequences of climate variability and climate change for the

United States based on two different global climate models (GCMs), RCMs were rarely applied in that study. Importantly, that report, as well as others, has highlighted the need for additional investigations of possible future, *regional climate changes* and climate impacts (e.g., *Easterling et al*., 2000).

This study is motivated by preliminary projections of substantially great climatic variations in California associated with global warming in the next few decades. In a recently published study (*Snyder et al.,* 2002), we found that temperature in the state likely will increase greatly (2-9°F temperature increase annually) in the next four decades, that snowpack will be reduced by up to 60%, and that rainfall throughout the state will remain nearly constant. The motivation is further catalyzed by projections of a near doubling of California's population within the next four decades, when its water resources are already limited. These projections of climatic change and population growth in California are projected to exacerbate current stresses on natural and human systems throughout the state, and they demand that we try to assess future climate change in the region.

The application of RCMs to investigations of possible future climate change is necessary because GCMs, while capable of running at relatively high resolution, are too computationally intensive to allow equilibrium calculations to be performed with the spatial scale necessary to resolve critical regional features such as mountain peaks, basins, and lakes (e.g., *Dickinson et al*., 1989). In addition, many model representations of subgridscale processes are not appropriate at regional and finer scales (e.g., *Risbey and Stone*, 1996). Methods for downscaling GCM results are also being applied to the issue of future climate change, but these efforts rely upon GCMs to a greater degree than do RCM calculations, and are more problematic to apply, especially in the case of precipitation.

Given the spatial variability and climatic complexity of California, we propose to use a GCM and a RCM to evaluate plausible potential future climate change scenarios for California, and present our results in a framework meant to facilitate use by institutions and individuals who are interested in water policy and planning activities in the state.

California is currently extremely vulnerable to changing climate, by the nature of the coastal and latitudinal orientation of the state, the wide variety of microclimates and ecosystems that are contained within the state, the large and growing population (32.1 million in 1995, estimated to grow to 47.5 million by 2020) *(DWR*, 1998), and the rich agricultural resources contained in California. California is especially vulnerable where water is considered, across the scope of water uses. Water resources in California currently depend upon reliable and fairly constant rainfall and snowfall seasons; any major perturbation to that system represents a severe risk to many aspects of the state (e.g., population growth, agriculture, tourism, industry, power generation). This vulnerability, and the uncertainty associated with future climate change, underscores the importance of studying climate change on a regional scale, and making those results available in accessible form, especially if responses to climate change are to be undertaken in an informed manner.

## Objectives

The objectives of the proposed research are (1) to drive a RCM with a GCM series of transient climate results for periods of the next century (~2000-2100), and (2) to analyze the model results within the framework of the 10 hydrologic regions that encompass the state as defined by the Department of Water Resources. The specific questions that we will focus on are: (1) how will anthropogenically driven climate change affect California's climate, especially the hydrologic resources, in the coming decades?; and (2) what water resources will be available in the future, and at what times during the year (e.g., seasonality and amounts of rain and snow)? The scope of this research will encompass several climate modeling sensitivity studies and in-depth analyses of the model results.

## Procedure (Methods)

We used a modified version of the RegCM2 RCM [*Giorgi et al.*, 1997; *Giorgi and Shields*, 1999; *Jenkins and Barron*, 2000; *Kato et al.*, 2001; *Small et al.*, 1999; *Sun et al.*, 1999] (hereafter referred to as RegCM2.5) for this study. 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 gridcells in the north-south direction and 55 gridcells in the east-west direction. The vertical resolution was set at 14 levels (Figure 1).

We used CCM3 (Version 3.6.6) [*Kiehl et al.*, 1998] to produce the boundary conditions for the RCM. This model was configured with a horizontal resolution of 2.8° latitude by 2.8° longitude. The model has 18 vertical levels. We first used a version of the model with a slab ocean-thermodynamic sea ice model. We performed two 18-year simulations 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 hereafter 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-hourly frequency 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 $pCO_2$ doubling.

The RCM has been validated against observations of modern day climate. We find 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 DJF; 2.4˚C for MAM; -0.4˚C for JJA; and –0.5˚C for 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% of the 540 individual observations that were used in the evaluation.

## Results

The output from the RCM was subdivided into the ten hydrologic regions as defined by the California Department of Water Resources [*DWR*, 1998] (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, and we focus on a comparison of results for the 1X case and the 2X case. We chose to report values 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, we use the median for consistency.

### *Changes on an Annual Basis*

For all hydrologic regions, the median annual temperature increases in the range of 1.9 to 4.0 °C (Table 1) (2X results versus 1X results). Temperature changes are statistically significant at the 95% 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%), while the four northernmost regions show minor increases (0.5 to 7.1%). 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 most northern 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% 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:

Our 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% 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).

#### 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% 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

## Conclusions

Our results 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 ten hydrologic regions of the state, provide a comprehensive picture of future climate in California from a regional perspective. According to our results, high elevation regions will be most severely impacted by temperature and moisture responses.

On an annual basis, our results 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, storage and delivery systems will be greatly perturbed by these changes.

Our 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 we would like to further examine the relationship between elevation and changing climate, especially for the state of California and other topographically complex regions. As was discussed earlier, our 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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## Tables

**Table 1:** Changes by regions: 2X case minus 1X case – Annual Average (Temperature in°C, precipitation percent change, and snow accumulation as percent change). The values highlighted in bold are significant at the 95% 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.

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

**Table 2:** Monthly Median Temperature Difference (°C): 2X minus 1X case. The values highlighted in bold are significant at the 95% confidence interval based on a paired T-test. Regions are the same as in Table 1.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | **1.50** | **1.49** | **2.25** | **1.64** | **2.37** | **1.98** | **1.77** | **3.75** | **2.88** | **3.03** |
| Feb | **3.98** | **2.90** | **4.65** | **3.26** | **4.07** | **3.75** | **2.33** | **4.96** | **3.05** | **3.81** |
| Mar | **3.76** | **3.11** | **3.89** | **3.55** | **4.35** | **3.74** | **2.77** | **3.97** | **3.45** | **3.05** |
| Apr | **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** |
| Jun | **2.07** | **2.50** | **2.99** | **2.39** | **3.14** | **3.40** | **2.13** | **3.69** | **2.97** | **2.13** |
| Jul | **2.27** | **1.80** | **3.12** | **1.71** | **2.64** | **2.73** | **2.00** | **3.34** | **2.76** | **2.91** |
| Aug | **2.36** | **3.21** | **3.93** | **2.02** | **3.46** | **2.73** | **1.88** | **2.96** | **2.53** | **2.76** |
| Sep | **2.76** | **2.90** | **2.84** | **2.55** | **2.96** | **2.68** | **2.45** | **2.55** | **2.61** | **2.57** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Oct | **1.54** | **1.92** | **1.41** | **1.60** | **1.27** | **1.30** | **2.26** | **1.01** | **1.31** | **1.54** |
| Nov | **1.42** | **1.33** | **1.26** | **0.85** | **1.24** | **1.15** | **0.97** | **1.23** | **1.07** | **1.03** |
| Dec | **1.32** | **1.46** | **2.11** | **0.86** | **1.29** | **1.23** | 0.83 | -0.17 | 1.94 | 1.10 |

**Table 3:** Monthly Median Precipitation Difference (mm/day): 2X minus 1X case. The values highlighted in bold are significant at the 95% confidence interval based on a paired T-test. Regions are the same as in Table 1.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0.649 | 0.205 | 0.177 | 0.068 | -0.069 | -0.731 | -0.128 | -0.117 | -0.130 | 0.080 |
| Feb | -0.044 | -0.045 | -0.028 | 0.247 | -0.299 | -1.317 | -0.761 | 0.119 | -3.009 | -2.929 |
| Mar | -0.646 | -0.286 | -0.201 | -1.512 | -0.884 | -2.704 | -1.791 | -0.307 | -2.189 | -0.912 |
| Apr | -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 |
| Jun | 0.001 | 0.000 | 0.007 | -0.007 | -0.092 | -0.087 | -0.005 | -0.243 | -0.162 | -0.047 |
| Jul | -0.012 | 0.000 | 0.002 | 0.000 | 0.017 | 0.003 | 0.000 | 0.004 | 0.002 | -0.033 |
| Aug | 0.023 | -0.001 | 0.022 | 0.016 | 0.041 | 0.013 | 0.000 | 0.010 | 0.000 | -0.002 |
| Sep | 0.034 | -0.012 | 0.029 | 0.001 | 0.012 | -0.001 | 0.000 | -0.008 | -0.005 | -0.064 |
| Oct | -0.003 | 0.000 | -0.009 | -0.007 | 0.000 | 0.032 | -0.017 | -0.017 | -0.089 | -0.344 |
| Nov | 0.208 | 0.127 | 0.102 | 0.144 | 0.345 | 0.126 | 0.542 | 0.129 | 0.344 | -0.284 |
| Dec | -0.507 | -0.133 | -0.187 | -1.062 | -2.045 | -3.217 | -0.555 | -0.598 | -2.615 | -1.144 |

**Table 4:** Monthly Median Snow Height Difference (mm snow water equivalent: 2X minus 1X case. The values highlighted in bold are significant at the 95% 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.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0.0 | -0.1 | -4.4 | NA | **-23.7** | **-72.8** | NA | **-19.7** | **-55.0** | **-45.7** |
| Feb | -0.1 | -0.1 | **-2.8** | NA | **-37.1** | **-88.6** | NA | **-35.3** | **-99.1** | **-68.6** |
| Mar | NA | NA | **-1.2** | NA | **-45.2** | **-109.0** | NA | **-60.6** | **-171.8** | **-110.6** |
| Apr | 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** |
| Jun | NA | NA | NA | NA | NA | -1.1 | NA | NA | NA | NA |
| Jul | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Aug | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Sep | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Oct | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Nov | NA | NA | NA | NA | 0.2 | -0.2 | NA | -0.4 | -2.4 | **-2.8** |
| Dec | NA | NA | NA | NA | -2.0 | -16.0 | NA | 6.6 | -8.1 | -6.6 |

**Figure 1:**

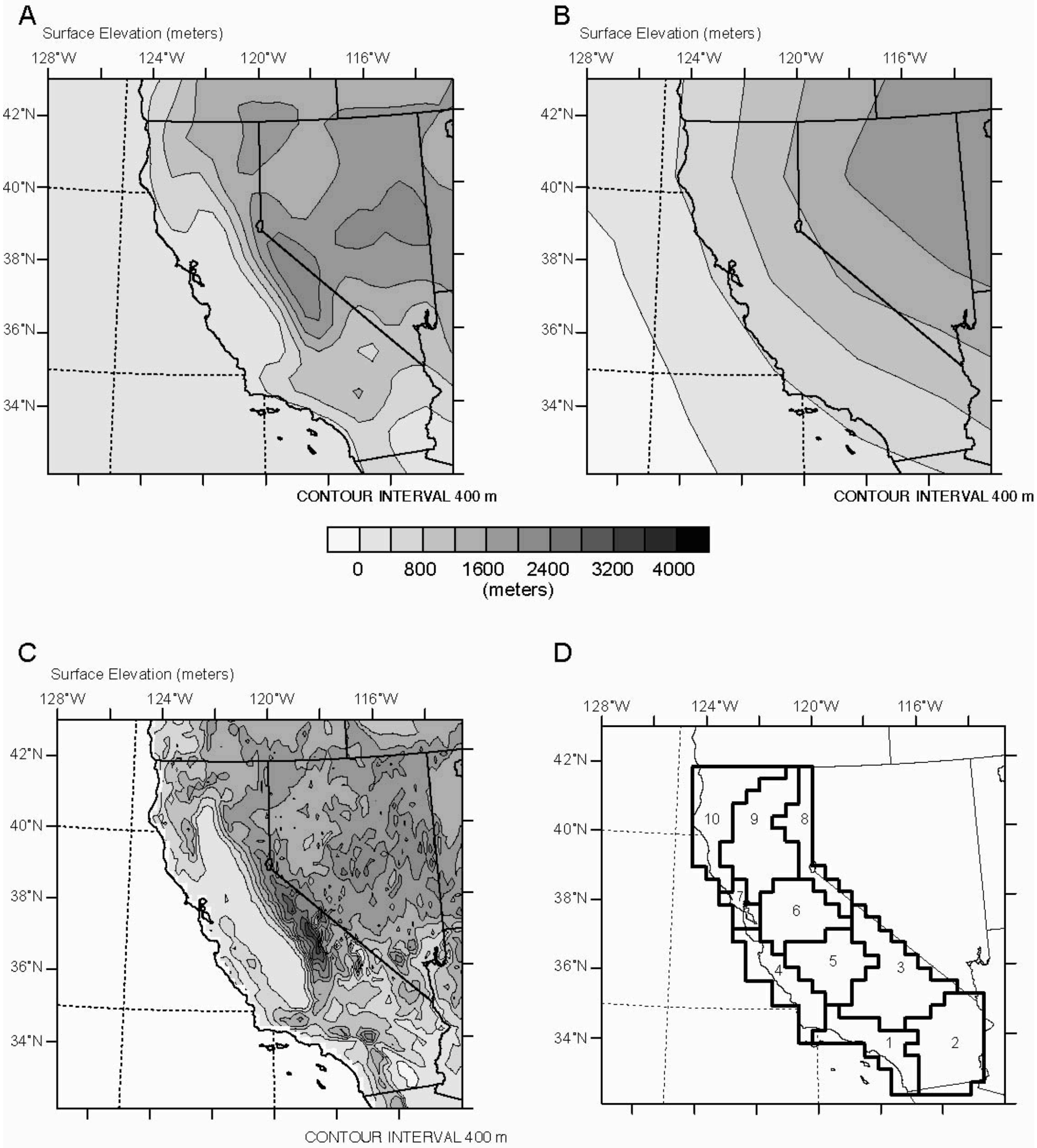
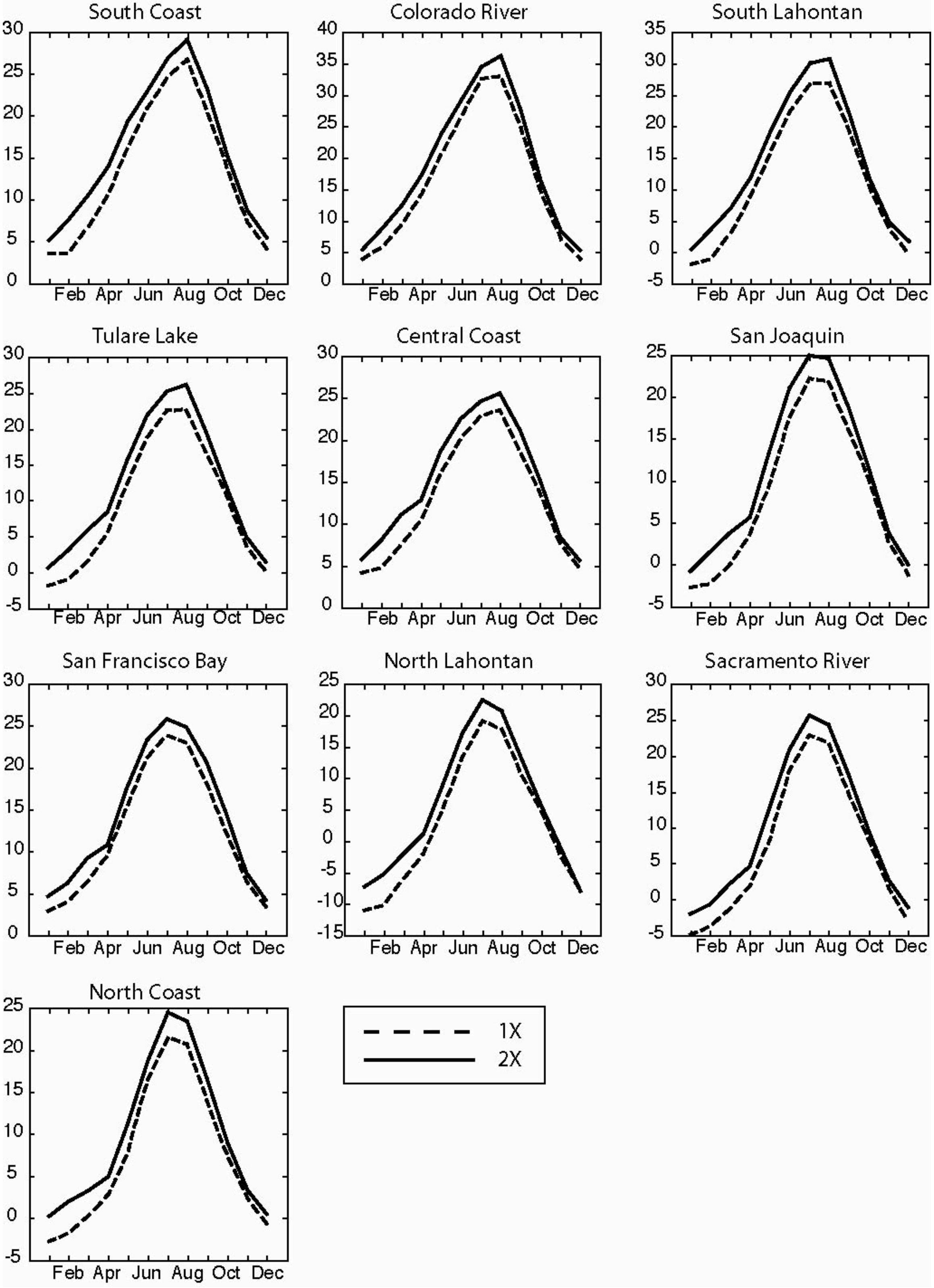


**Figure Caption:** Topography of California and map of the ten hydrologic regions of California. (A) Topography of the regional climate model (RegCM2.5). (B) Topography of the global climate model (CCM3). (C) 10 minute resolution topography of California. (D) The ten hydrologic regions of California 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; (10) North Coast.

**Figure 2:**



South Coast

Colorado River

South Lahontan

Tulare Lake

Central Coast

San Joaquin

San Francisco Bay

North Lahontan

Sacramento River

North Coast

**Figure Caption:** 1X and 2X monthly surface temperature (Celsius) by region.

**Figure 3:**

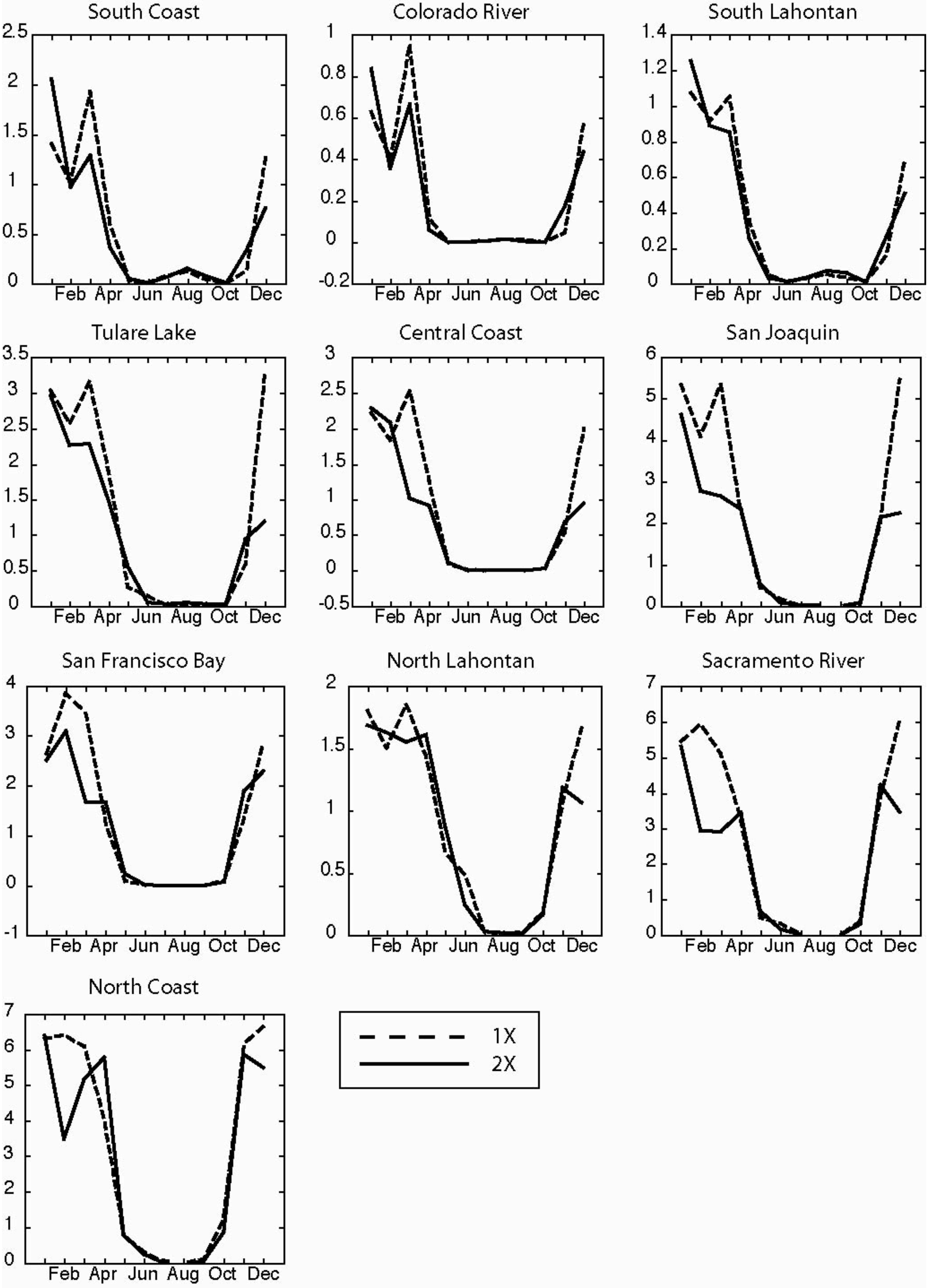


**Figure Caption:** 1X and 2X median monthly precipitation (mm/day) by region.

**Figure 4:**

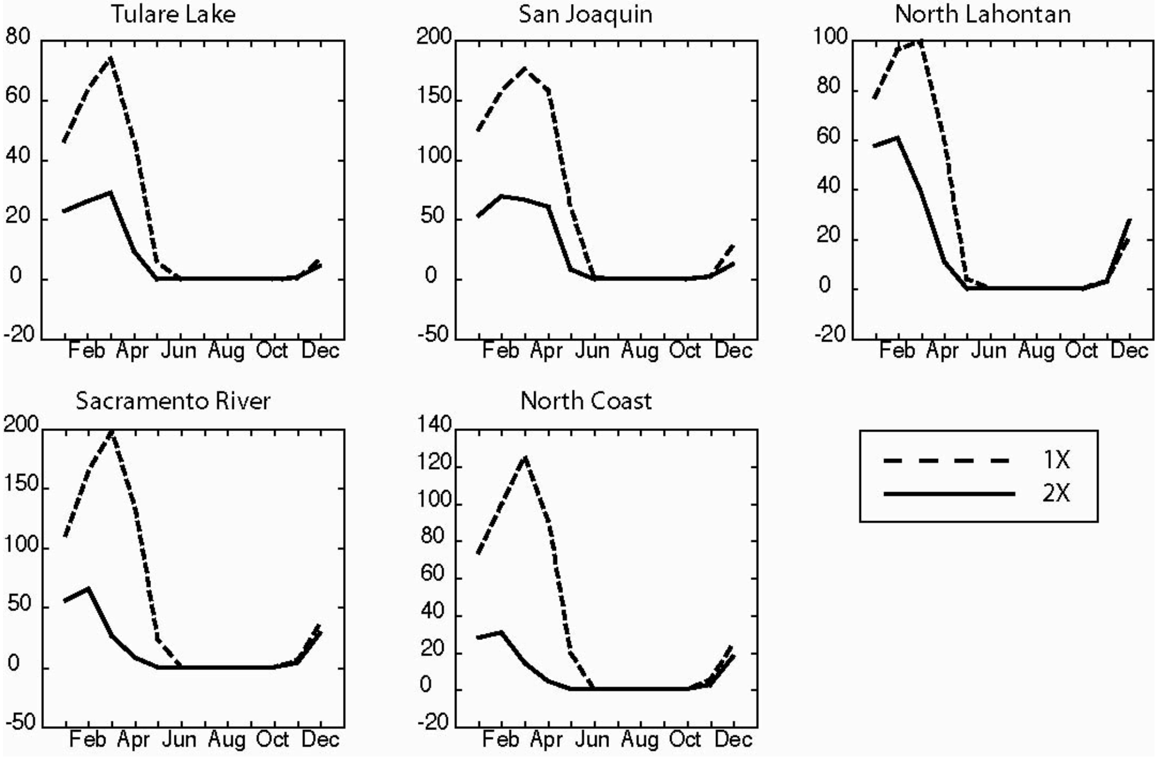


**Figure Caption:** 1X and 2X median monthly snow accumulation (mm snow water equivalent) by region.

## Publications

Modeled Regional Climate Change in the Hydrologic Regions of California: A $CO_2$ Sensitivity Study, Snyder, M.A., Sloan, L.C., and Bell, J.L., Jour. American Water Resources Assoc., 591-601, 2004.