Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region

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[1] Global modeling studies of future climate change predict large scale climatic responses to increased atmospheric carbon dioxide (CO_2). While there have been several regional climate modeling studies that produced results at spatial and temporal scales relevant for climate change impact analysis, few have employed statistical significance testing of results. In a sensitivity study that focused on mean climate states, we use a regional climate model to generate ensembles of climate scenarios under atmospheric conditions of 280 and 560 ppm CO_2, for a domain centered over California. We find statistically significant responses by mean annual and monthly temperature, precipitation, and snow to CO_2 doubling. Relative to the 280 ppm results, 560 ppm results show temperature increasing everywhere in the region annually (up to 3.8°C), and in every month, with the greatest monthly surface warming at high elevations. Snow accumulation decreased everywhere, and precipitation increased in northern regions by up to 23%, on a mean annual basis. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 9350 Information Related to Geographic Region: North America; 1854 Hydrology: Precipitation (3354); 1699 Global Change: General miscellaneous

1. Introduction

[2] Atmospheric carbon dioxide (CO_2) is projected to surpass a doubled preindustrial value well before year 2100, and possibly as soon as 2050 [*Intergovernmental Panel on Climate Change. Working Group I*, 2001]. Based upon projected rates of carbon emissions and atmospheric greenhouse gas (GHG) increases [*Intergovernmental Panel on Climate Change. Working Group I*, 2001] and global climate model (GCM) results, the most recent Intergovernmental Panel on Climate Change (IPCC) report estimates an increase of 1.4–5.8°C in global mean temperature over the next century. Regional temperature responses could be even larger, because regional responses to increasing GHG concentrations can vary significantly relative to the mean global response ([e.g., *Easterling et al.*, 1997; *Giorgi et al.*, 2001]). As a result, the application of regional climate models (RCMs) to investigations of possible future climate change are necessary because GCMs typically are too computationally intensive to be used at spatial scales that resolve critical regional topographic features ([e.g., *Dickinson et al.*, 1989]).

[3] Several recent reports emphasize the need for detailed investigations of possible future climate change at regional scales [e.g., *Giorgi*, 1995; *Easterling et al.*, 2000; *National Assessment Synthesis Team*, 2001]. However, studies with RCMs with high temporal detail and spatial resolutions exceeding 45 km resolution are relatively rare to date [*Giorgi et al.*, 1997; *Lettenmaier et al.*, 1999; *Christensen et al.*, 2001; *Kim*, 2001]. Note there are also various methods of downscaling GCM results, but we focus here only on regional climate modeling and the resolution of those studies.

2. Study Area

[4] To explore this issue we focus on western North America, specifically California, in this study. We chose California as an initial case because it is currently extremely vulnerable to changing climate. This vulnerability is due to the coastal and latitudinal orientation of the state, the wide variety of microclimates, environments, and ecosystems, the large and growing population (32.1 million in 1995, estimated to grow to 47.5 million by 2020) [*Cal. Dept. of Water Resources*, 1998], and the rich agricultural resources ($26.8 billion in 1997, the highest yield of all states). California is especially vulnerable where water is considered, in part because nearly all precipitation is received between November and April.

3. Model Descriptions and Experiment Design

[5] Our study differs from other regional climate modeling studies of future scenarios in several ways. First, this is the only RCM study we know of that included multiple runs with the same model (ensemble approach, explained below) for each scenario. Second, we compare results of two ensembles of experiments that differ only in the specified, steady state CO_2 concentrations. Lastly, we incorporated a finer spatial resolution (40 km gridcell length) than that used in most other RCM studies.

[6] We used a modified version of the RegCM2 RCM [*Giorgi and Shields*, 1999] (hereafter referred to as RegCM2.5) for this study. RegCM2.5 contains the radiation code of Community Climate Model (CCM3), which is an

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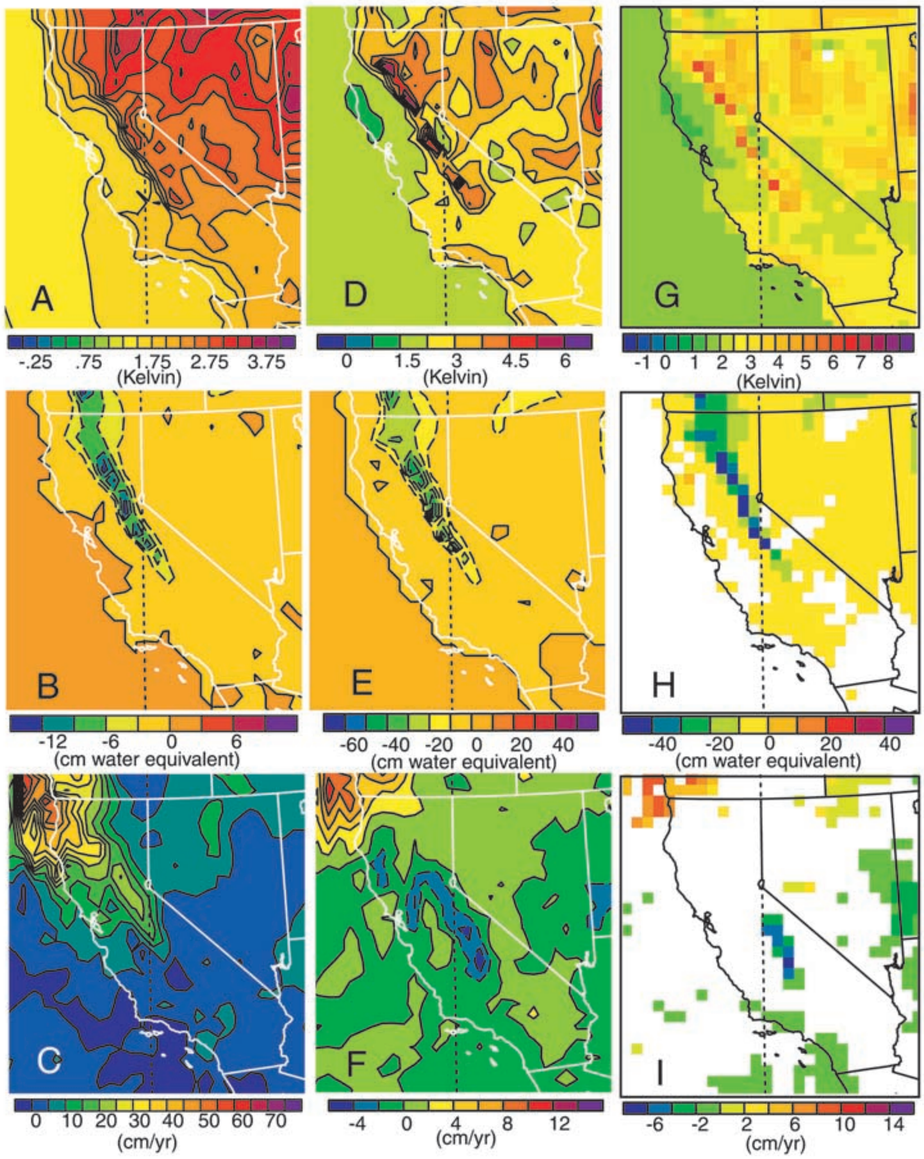

Figure 1. Difference for $2xCO_2$ minus $1xCO_2$ cases in average results for (a) annual surface temperature (degrees Kelvin), (b) annual SWE (cm), (c) annual precipitation (cm/yr), (d) April surface temperature, (e) April SWE, (f) April precipitation; statistically significant differences in average results for (g) April surface temperature, (h) April SWE, (i) April precipitation. White areas in panels (g) through (i) indicate mean differences are not significant at 95% confidence based on the U test. Domain shown is a subset of the total regional model domain used in the study.

improvement over the previous version of RegCM. The model uses the BATS (version 1e) surface model [*Dickinson et al.*, 1993].

[7] We used CCM3 (Version 3.6.6) [*Kiehl et al.*, 1998] as our primary global driver. This spectral model was configured with 42 surface spherical harmonics; the horizontal resolution is $\sim$2.8° in latitude and 2.8° in 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 15-year simulations. 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 $1xCO_2$ and $2xCO_2$ cases, respectively). All other boundary conditions were set to present values. Because model output was saved at monthly frequency, the resulting SSTs were used in a second pair of CCM3 experiments with prescribed SSTs and corresponding levels of atmospheric CO_2. Results from these cases were saved at 12-hourly frequency for input to RegCM2.5. CCM3 was run for 12 years for each case, and the last 8 years of model output were used to drive the regional model.

[8] RegCM2.5 was run at 40 km horizontal resolution with a domain centered over California (Figure 1). An ensemble of 3 cases of the regional model was run for each CO_2 scenario. Each ensemble member was initialized from a different time in the CCM integration, with each initialization date at least 15 days apart. We used this method to explore the usefulness of performing RCM ensembles, versus carrying out fewer, longer runs, or carrying out

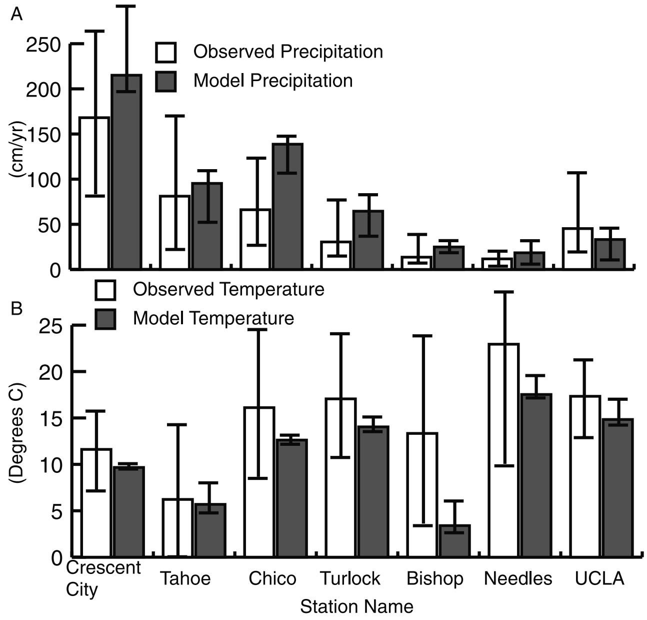

Figure 2. Comparison of modern day RegCM2.5-produced annual average temperature (degrees C) and precipitation (cm/yr) with observational data. Columns show annual average precipitation (A) and temperature (B) for the period of record at each station and from the model. Lines show range of each variable from observations and the model.

ensembles with the global model. Each RegCM2.5 case was run for a total of 8 years. Results of the monthly averages from the final 5 years for each ensemble are presented here.

4. Evaluation of Model Performance

[9] As an evaluation of our ability to simulate California's present climate, an additional pair of GCM and RCM cases were carried out using modern day initial and boundary conditions. CCM3 was run with climatological SSTs for the a period of 18 years and results were used to drive RegCM2.5 (as above). Results of the final 15 years of the RCM run were used for analysis. The results compare well to observations of temperature, precipitation, and snow accumulation (Figure 2). Differences that occur between model-produced and observed temperatures can be explained largely by differences in the model elevation of the station and the true elevation. Modeled snow water equivalent (SWE) compares well with observations; overestimation of SWE occurs where model elevation is significantly different from true elevation. Simulated annual precipitation values are within the range of observed interannual variability for all but 1 station (Figure 2).

5. Results

[10] Annual average results show temperature increases of 1.4–3.8°C everywhere across the region under $2xCO_2$ conditions (Figure 1). The results also reveal a decrease in snow accumulation by up to 120 mm SWE, and an increase in annual average precipitation by up to 43.2 cm/yr (~23% increase) across the northern half of the state.

[11] Monthly results show much larger temporal and spatial variability of response in many regions and indicate climate characteristics that are not evident in the mean annual results. For example, in April, while there is warming everywhere in the region, warming is greatest at high elevations of the Sierra Nevada Mountains (SNM) and the Cascade Range, with temperature increasing by up to 6.3°C from the $1xCO_2$ to the $2xCO_2$ scenario (Figure 1). In May the temperature increase in these areas is as large as 9.2°C (not shown). In March, precipitation in the northern half of the state increases by up to ~16 cm/mon (~100% increase, not shown). In April, the central SNM experience a reduction in precipitation of as much as 3.6 cm/mon (67% decrease) (Figure 1). Snow accumulation by the end of February is approximately 360 mm SWE less in the $2xCO_2$ case (an 82% decrease). By the end of April snow accumulation is approximately 520 mm SWE less, representing a nearly 100% decrease from $1xCO_2$ values.

6. Discussion and Conclusions

[12] It is important to assess the statistical significance of differences between the $1xCO_2$ and $2xCO_2$ results in order to distinguish between actual climate change and internal climate variability. We use the Mann-Whitney U test in our analysis of statistical significance (see Appendix). We find that the annual average temperature change is significant at 95% confidence levels over the entire region and major annual precipitation and snow differences are significant in areas of greatest change (not shown). On a monthly basis, the major features of all of the results are significant at the 95% confidence level (e.g., Figure 1).

[13] In the future, as regional climate modeling is applied more extensively to scenarios of future climate change, it will be important to be able to assess results across different models. To this end, we suggest that statistical testing such as outlined here be used routinely in regional climate modeling analyses.

[14] Regarding the ensemble approach that we used in this study, we find small variability between the ensemble results. There is an order of magnitude greater temperature difference between different years of a run versus between years of ensembles. Our results suggest that longer runs are better than multiple regional climate modeling runs forced in the manner used here.

[15] Our results for the California region demonstrate the need to address regional climate change scenarios on monthly and shorter timescales and to apply a high-resolution regional approach to studying climate change scenarios. Applying this modeling approach to other regions is likely to reveal vulnerabilities to future climate change that are not evident currently.

Appendix

[16] We use the Mann-Whitney U test, the nonparametric analog of the t test, for our analysis of statistical significance. The t test assumptions are false for the data populations generated by this study. The impact of highly variable and extreme data values, such as precipitation and snow accumulation, on the U statistic is reduced

because the U test does not account for variance, only data rank order.

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