Regional Changes in Extreme Climatic Events: A Future Climate Scenario

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ABSTRACT

In this study a regional climate model is employed to expand on modeling experiments of future climate change to address issues of 1) the timing and length of the growing season and 2) the frequency and intensity of extreme temperatures and precipitation. The study focuses on California as a climatically complex region that is vulnerable to changes in water supply and delivery. Statistically significant increases in daily minimum and maximum temperatures occur with a doubling of atmospheric carbon dioxide concentration. Increases in daily temperatures lead to increases in prolonged heat waves and length of the growing season. Changes in total and extreme precipitation vary depending upon geographic location.

1. Introduction

Analysis of long-term temperature and precipitation records has revealed changes in the mean climatic state as atmospheric carbon dioxide (CO_2) levels have increased since the industrial revolution (Easterling et al. 1997; Gaffen and Ross 1998; Plummer et al. 1999; Salinger and Griffiths 2001). Research employing global climate models (GCMs) indicates potentially greater changes for future climate states (Cao et al. 1992; Zwiers and Kharin 1998; McGuffie et al. 1999; Yonetani and Gordon 2001). Changes in the mean climate state have been found to affect the frequency and intensity of extreme climatic events as well (Mearns et al. 1984; Katz and Brown 1992; Groisman et al. 1999; Meehl et al. 2000). Extremes in temperature and precipitation have important impacts on vital aspects of society, including crop yield, power consumption and production, and human health (Easterling et al. 2000; Meehl et al. 2000; Walther et al. 2002). Responses to climate change and mitigation of negative impacts must be resolved at regional and local levels in order for effective action to be taken; therefore, it is important to assess the potential for climate change on a regional level.

Regional changes in climate are highly variable and cannot be adequately represented by GCMs at this time. This inability necessitates the use of regional climate models (RCMs) to address potential climate change on the regional scale. Snyder et al. (2002) used an RCM to demonstrate the potential for significant changes in the mean climate of the California region due to a doubling of atmospheric CO_2 levels. The present study addresses potential changes in the frequency and intensity of extreme daily temperatures and precipitation events for the same region and CO_2 scenarios.

2. Model description and experiment design

The model description and experiment design is similar to that of Snyder et al. (2002) with a few key differences. Snyder et al. (2002) performed a sensitivity study of California climate with doubled CO_2 using a limited ensemble approach. The limited ensemble approach utilized identical GCM boundary conditions with multiple RCM simulations. Two CO_2 scenarios were compared and each scenario was comprised of three ensemble members of 5 years in length. While this approach was successful at limiting computational expense the results indicate that the GCM is responsible for the majority of the variability. Snyder et al. (2002) discovered that the year-to-year variability within a given simulation was much greater than the variability between ensemble members. Based on these conclusions we use a single 15-yr simulation for each of the CO_2 scenarios and present results based on twice-daily model output.

We used the National Center for Atmospheric Research (NCAR) Community Climate Model version 3.6.6 (CCM3) (Kiehl et al. 1998) as the global driver for our regional model. We first used a version of CCM3 with a slab ocean–thermodynamic sea ice model to perform two 15-yr simulations. The two simulations differed only in the atmospheric CO_2 concentrations, which were 280 ppm (preindustrial level) and 560 ppm (hereafter referred to as $1 \times CO_2$ and $2 \times CO_2$ scenarios, respectively). Due to the model output only being saved at monthly intervals the calculated sea surface temper-

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atures (SSTs) were used to drive a second set of CCM3 simulations. These simulations, using the prescribed SSTs for the corresponding CO_2 concentrations, were run for 22 years and results were saved at 12-h intervals. The first 4 years of each simulation were removed as equilibration time and the remaining 18 yr of results were used to drive the RCM.

This study employs a modified version of the second-generation NCAR Regional Climate Model (RegCM2) (Giorgi and Shields 1999) (hereafter referred to as RegCM2.5) as described by Snyder et al. (2002). RegCM2.5 was run with a horizontal resolution of 40 km and a domain centered over California. We performed two 18-yr simulations with the first three years removed for equilibration. These simulations varied only in the specified atmospheric CO_2 concentrations (280 and 560 ppm).

3. Validation

It is important when discussing the need for more regional and local scale studies of climate change and impacts to be able to demonstrate the capability for such studies. Here we demonstrate 1) the ability of the regional model to adequately capture both the general (seasonal temperature and precipitation) and specific [diurnal temperature range (DTR), growing season length, frequency and intensity of extreme events] characteristics of regional climate observed for the modern day and 2) that regional models are currently better suited for this type of analysis than global models. Mearns et al. (1999) have performed a similar validation for RegCM2 with a domain centered on Nebraska while Snyder et al. (2002) performed a more general validation over California.

a. Modern climate

Here we compare the results of a modern-day regional climate simulation to observations. The model simulation of present-day conditions is similar in design to our $1 \times CO_2$ and $2 \times CO_2$ scenarios. CCM3 was run for 22 years forced with a single climatological year of SSTs (calculated from observations for the period from 1950 to 1979). The first 4 yr were removed for equilibration and the last 18 yr were used to drive RegCM2.5. The first 3 yr of the RegCM2.5 simulation were removed for equilibration and the last 15 yr are used for the analysis presented here. The atmospheric CO_2 concentration in both models was 360 ppm.

The observational data used are historical weather station data collected by the Western Regional Climate Center (2003). The types and scope of data available vary depending on the climate characteristics of interest. For each comparison with the model results we treat all data in as similar a manner as possible. For the analyses of seasonal temperature and precipitation we used climatological data calculated with a minimum of 22 yr

TABLE 1. Summary of comparison between observations (obs) and RegCM2.5 (rcm) modern-day simulation.

	obs	rcm	obs−rcm
Temperature			
Annual mean (°C)	32.7	32.0	0.7
DJF (°C)	25.3	23.9	1.4
MAM (°C)	31.4	29.0	2.4
JJA (°C)	40.4	40.8	−0.4
SON (°C)	33.6	34.1	−0.5
$T \geq 32.2$°C (days)	71.4	43.8	27.6
$T \geq 0$°C (days)	68.5	38.2	30.3
1-day max (°C)	44.1	40.1	4.0
1-day min (°C)	−15.2	−12.9	−2.3
DTR			
Annual mean (°C)	15.4	9.7	5.7
DJF (°C)	12.2	6.0	6.2
MAM (°C)	15.0	9.2	5.8
JJA (°C)	18.3	13.4	4.9
SON (°C)	15.9	10.2	5.7
Precipitation*			
Annual mean (cm)	52.9	56.7	−3.8
DJF (cm)	26.6	31.6	−5.0
MAM (cm)	13.9	16.6	−2.7
JJA (cm)	2.2	0.5	1.7
SON (cm)	8.6	8.1	0.5
Light (days)	88.9	97.1	−8.2
Moderate (days)	12.3	13.3	−1.0
Heavy (days)	5.5	5.7	−0.2
1-day max (cm)	12.1	10.8	1.3

* Precipitation intensities are defined as: light days < 1.27 cm, moderate days < 2.54 cm, and heavy days ≥ 2.54 cm.

of data from the period 1971–2001. For the more specific analyses (DTR, growing season, and extremes) the available data ranges from 27 to 100 yr in length (on average 49.4 yr) for the period from 1901 to 2001. We began our analysis with ~55 stations and, due to the shear volume of available data, narrowed it to stations where the actual and model-derived elevations differed by no more than 100 m. What remained were 16 stations representing a wide range of latitude, longitude, and elevations across California.

Overall the comparison between modern-day regional model results and weather station data is very good. This is especially the case considering the data record is much longer than the model simulation and therefore provides a larger sample population. Furthermore the weather stations provide point data, while the model results are derived from single grid cells with 40-km horizontal resolution. Still there are some issues with the model results, especially for the DTR and the seasonality of precipitation.

The regional model adequately captures the seasonal changes in temperature as well as the annual mean temperature. On average the RCM is only 0.7°C cooler for the annual mean and no more than 2.4°C different seasonally than the observations (Table 1). The RCM more accurately captures the summer [Jun–Aug (JJA)] and fall [Sep–Nov (SON)] temperatures than the winter [Dec–Feb (DJF)] and spring [Mar–May (MAM)] temperatures. The DTR is too small by ~5° to 6°C annually and seasonally (Table 1). The growing season starts on average 16.5 days too soon and ends 13.8 days too late. For extremes the model simulates ~28 too few hot (32.2°C) days per year and ~30 too few cold (0°C) days per year (Table 1). While the model simulates too few extreme events it does not overestimate the intensity of simulated extreme events. The historic 1-day events simulated by the model fall within the range of historic events in the longer observational record (Table 1).

The regional model outputs temperature twice a day at noon and midnight. These temperatures are used as proxies for the daily maximum and minimum and are not the actual maximum and minimum temperatures. As a result, the proxy maximum temperatures are too cool and the proxy minimum temperatures are too warm, producing a dampened DTR. The use of the proxy minimum also affects the calculated beginning and end of the growing season. The growing season appears to start earlier and end later due to the use of the proxy minimum temperature. Finally the use of these proxy temperatures results in extreme events that do not appear as extreme as those in the observational record.

Annually the regional model slightly overestimates total precipitation (+3.8 cm yr^{-1}) and poorly captures the seasonality of precipitation. The model overestimates winter and spring precipitation and underestimates summer and fall precipitation (Table 1). The model also simulates ~8 too many light rainfall days per year (<1.27 cm day^{-1}). For moderate (1.27–2.54 cm day^{-1}) and heavier (>2.54 cm day^{-1}) rainfall days the model is much more accurate (Table 1). The model simulates one day too many per year of moderate precipitation and only 0.2 too many days per year of heavier rainfall. The model does a good job simulating historic 1-day events considering the differences in sample sizes. The average 1-day high is 1.3 cm less in the model than in the observations (Table 1).

b. GCM versus RCM

A RCM offers higher spatial resolution than a GCM, allowing for greater topographic complexity and smaller-scale atmospheric dynamics to be simulated and investigated. Theoretically, higher resolution should lead to more realistic simulations of regional-scale climate. The biggest weakness with RCMs is the dependence on lateral boundary input either via GCM, reanalysis, or observational data. If an RCM receives poor quality input it is not likely to output much higher quality results. So, if quality GCM input is needed, then is the use of an RCM necessary? The answer to that question depends on the inquiry to be addressed. Obviously a RCM would be inadequate to address issues of global, or even hemispheric, changes in atmospheric circulation. Likewise a GCM may not be appropriately suited for questions that are subcontinental in scale, especially for complex regions. California is a climatically and topographically complex region and therefore a study of the regional climate there warrants the use of a RCM.

Having already demonstrated that RegCM2.5 does a good job of simulating the modern observed climate of California we must answer another question: Does the RCM do a better job of simulating California climate than the GCM? The modern-day CCM3 simulation was analyzed in the same manner as the RCM output. We compared the CCM3 results for temperature and precipitation to the 16 weather stations discussed earlier. For over 540 individual comparisons of GCM and RCM versus observational data the GCM compared more favorably than the RCM only 25% of the time. Furthermore there was no one specific climatic feature or characteristic that the GCM consistently simulated better than the RCM. Clearly there is utility in using the RCM, and not just the GCM, to address issues of changes in climate for a complex region.

Overall RegCM2.5 does a good job simulating the main features of the modern-day climate, though it is not perfect. RegCM2.5 also does a much better job simulating the California climate than CCM3. Any inherent biases in RegCM2.5 will be present in both of our CO_2 scenarios. Therefore, since this is a sensitivity study, these model biases will be mitigated when calculating changes in the climate due to the doubling of CO_2.

4. Analysis methods

California spans a wide latitudinal range and contains a variety of microclimates. Due to this diversity of microclimates, we perform our analysis on the hydrologic basin scale, as defined by the California Department of Water Resources (1998) (Fig. 1). The methods for analysis of changes in extreme events are similar to those of Salinger and Griffiths (2001). Annual extreme events are defined based on the 5th and 95th percentiles of the $1 \times CO_2$ results.

a. Temperature

We define three types of extreme temperature events and examine changes between the $1 \times CO_2$ and $2 \times CO_2$ scenarios. The first type of extreme event is based on the 95th and 5th percentiles of daily maximum and minimum temperatures, respectively. These percentiles correspond to the 18th hottest maximum and coldest minimum temperatures in a year (based on the number of events per year multiplied by the percentile). For all 15 years of the $1 \times CO_2$ simulation the annual 5th-percentile events were averaged together to create a long-term extreme cold index value, likewise for the annual 95th-percentile events. These long-term indices are used for the evaluation of changes in extreme events. The second type of extreme event examined is based on specific temperature thresholds. We examine the frequency of events below 0°C and above 32.2°C. The third type of extreme event is a prolonged extreme event.

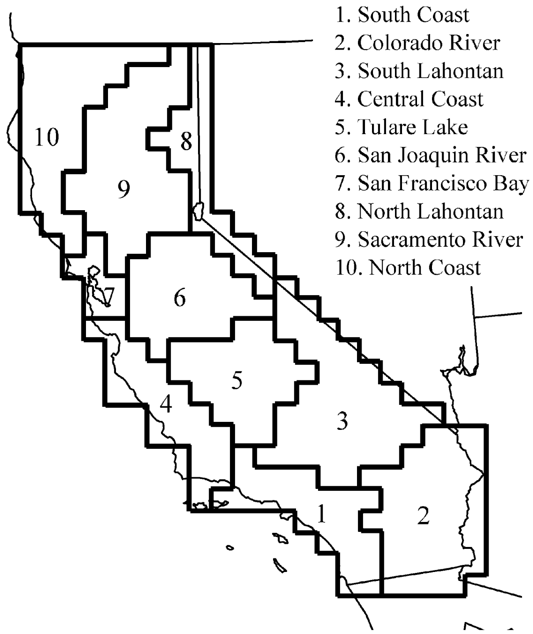

FIG. 1. The hydrologic basins of California shown here are adapted from the California Department of Water Resources (1998) to the 40-km RCM grid. Note the area shown here is a subset of the total regional model domain used in this study.

These are events where the maximum (or minimum) temperature exceeds the long-term 95th (or 5th) percentile for seven or more consecutive days.

Indices of temperature examined are the following:

- Changes in mean daily temperature maximum, minimum, and range: T_{max}, T_{min}, T_{range}, respectively.
- The frequency of days with maximum (minimum) temperatures above (below) the 95th (5th) percentile: T_{95} (T_{05}). (Extreme event of type 1 described above.)
- The frequency of days with temperatures above (below) 32.2°C (0°C): T_{32} (T_0). (Extreme event of type 2 described above.)
- Changes in prolonged extreme events, including frequency, mean length, and mean temperature of prolonged hot and cold extreme events. (Extreme event of type 3 described above.)
- Changes in the beginning and length of the annual growing season (based on the frost-free period).

b. *Precipitation*

Precipitation in California is highly variable on all temporal and spatial scales. For each basin we examine changes in daily and annual rainfall and the frequency of extremely heavy rainfall events. Heavy rainfall events are defined using the 95th percentile as explained above for extremely high temperatures.

Indices of precipitation examined are the following:

- Changes in mean annual rain.
- Changes in mean rain per rain day[1] and number of rain days per year.
- The frequency of extreme events exceeding the 95th percentile (as above): P_{95}.

5. Results

a. *Temperature*

In general the 2 × CO_2 scenario is hotter than the 1 × CO_2 scenario. For every basin the mean daily maximum and minimum temperatures are greater in the 2 × CO_2 scenario than in the 1 × CO_2 scenario (Table 2), with differences statistically significant at the 95% confidence level (5% significance level). While the increases in both maximum and minimum are similar, the increase in daily maximum is greater, for 9 of 10 basins, than the increase in daily minimum. This leads to an increased mean DTR in these regions. Although the change in DTR is relatively small, it is still significant in 7 of 10 basins (Table 2). Our results indicate an increase in extremely hot days (T_{95}), days exceeding 32.2°C, and in prolonged hot spells (Table 3). Not only are there more prolonged hot events in the 2 × CO_2 scenario, but these events are longer and hotter on average than the prolonged events in the 1 × CO_2 scenario (Table 3). While the maximum temperatures are rising in the 2 × CO_2 scenario, so are the minimum temperatures, resulting in a decrease in days below the 5th percentile (T_{05}) and in days below 0°C (Table 2). Due to the decrease in days with temperatures less than 0°C the frost-free period begins, on average, 25 days earlier in the 2 × CO_2 scenario and is on average 38 days longer. In our 2 × CO_2 scenario we also find that prolonged cold events occur less often and are shorter and warmer on average than in the 1 × CO_2 scenario.

b. *Precipitation*

We find decreases in mean annual rainfall across the state (Table 4). Only the North Coast and North Lahontan basins have increased rain, 1% and 3%, respectively. On average there is very little change in mean rainfall per rain day, although there are generally fewer rain days per year in each basin (~5 days). With the exceptions of the North Coast and North Lahontan basins there is also a decrease in extremely heavy rainfall (P_{95}) events as well (Table 4). On average, 2.4 fewer heavy events occur per year per basin, while the North Coast and North Lahontan basins average 2.5 *additional* heavy rainfall events per year compared to the 1 × CO_2 scenario.

[1] We define a rain day as any day with basin average of 0.1 mm or more of precipitation.

TABLE 2. Changes in annual temperature and frequency of 1-day extreme events. All Δ values are calculated as 2 × CO_2 results minus 1 × CO_2 results. Values in bold type indicate statistically significant results at the 95% confidence level (5% significance level). For basin names and locations see Fig. 1. Descriptions of the variables and methods of calculation are given in section 4, analysis methods.

	Basins									
	1	2	3	4	5	6	7	8	9	10
Δ T_{max} (°C)	**2.08**	**2.31**	**2.58**	**1.99**	**2.39**	**2.38**	**1.95**	**2.66**	**2.59**	**2.47**
Δ T_{min} (°C)	**1.99**	**2.24**	**2.40**	**1.93**	**2.22**	**2.26**	**1.97**	**2.51**	**2.43**	**2.33**
Δ T_{range} (°C)	**0.09**	0.07	**0.18**	0.06	**0.17**	**0.12**	−0.02	**0.15**	**0.16**	**0.14**
	Hot events									
T_{95} Index (°C)	32.5	40.2	34.7	30.9	30.8	29.7	31.6	25.8	30.0	28.3
Δ T_{95} (days yr^{-1})	**10.5**	**22.1**	**30.6**	**15.0**	**25.5**	11.2	**12.7**	**34.5**	**32.1**	**27.1**
Δ T_{32} (days yr^{-1})	**11.3**	**20.1**	**26.9**	**12.1**	**20.3**	**16.1**	**9.8**	**0.8**	**21.2**	**9.5**
	Cold events									
T_{05} Index (°C)	5.1	7.5	0.8	6.7	0.9	−0.1	6.1	−7.6	−1.9	−1.0
Δ T_{05} (days yr^{-1})	**−47.5**	**−43.6**	**−42.7**	**−57.3**	**−39.1**	**−34.9**	**−52.8**	**−29.6**	**−35.5**	**−36.9**
Δ T_0 (days yr^{-1})	**−15.1**	**−9.6**	**−38.3**	**−7.6**	**−34.3**	**−36.0**	**−12.2**	**−39.9**	**−47.4**	**−44.6**
	Growing season									
Δ First day	**−35.1**	**−21.6**	**−22.3**	**−34.1**	**−21.1**	**−26.6**	**−37.5**	**−9.1**	**−20.5**	**−24.9**
Δ Length (days)	**62.5**	**30.0**	**31.2**	**46.7**	**29.0**	**40.1**	**46.6**	**22.5**	**30.8**	**37.6**

6. Discussion

Several studies have examined extremes of temperature and precipitation on regional and global scales. These studies generally fall into two categories: 1) analysis of global (Easterling et al. 1997, 2000) and regional (Gaffen and Ross 1998; Plummer et al. 1999; Salinger and Griffiths 2001) observational records for the twentieth century and 2) climate modeling studies similar in concept to the present study (Cao et al. 1992; Mearns et al. 1995; Zwiers and Kharin 1998; McGuffie et al. 1999; Yonetani and Gordon 2001; Milly et al. 2002; Palmer and Raisanen 2002). These modeling studies are all global in scope with the exception of Mearns et al. (1995), discussed later. Both observational and modeling studies are useful but both have specific limitations. Observations are available at high spatial and temporal resolution for multiple decades allowing for precise and detailed analysis of recent changes in climate. Unfortunately observations generally only span the twentieth century and therefore include the effects of increasing greenhouse gases, population growth, and urbanization, all of which can influence climate. Due to the lack of records prior to the industrial revolution and the relatively short length of the observational record it is difficult to distinguish between climate variability and climate change. Although climate models have several inherent limitations ranging from computational expense to approximation of natural processes and incomplete representation of the entire earth system, they are the best tools available for describing potential features of future climates. Furthermore, with a climate model one can isolate a single variable and create a controlled experiment such as this.

In this experiment we used state-of-the-art climate models to expand on past modeling studies of future climate to address issues largely left to observational studies. These issues include the timing and length of the growing season and frequency and intensity of extreme temperatures and precipitation. This study differs from previous modeling studies with its high spatial and temporal resolution and the types of climate indices examined.

TABLE 3. Changes in prolonged (7-day) extreme temperature events. All Δ values are calculated as 2 × CO_2 results minus 1 × CO_2 results. Values in bold type indicate statistically significant results at the 95% confidence level (5% significance level). For basin names and locations see Fig. 1.

	Basins									
	1	2	3	4	5	6	7	8	9	10
	Prolonged hot events									
Δ Frequency (yr^{-1})	**0.8**	**1.0**	**1.1**	**1.0**	**1.2**	**1.6**	0.4	**1.5**	**1.5**	**1.6**
Δ Length (days)	0.1	**6.3**	**10.0**	0.7	**5.1**	**3.7**	0.5	**7.2**	**5.4**	**3.2**
Δ T_{mean} (°C)	0.6	**0.8**	**0.6**	0.8	**0.9**	**0.5**	**1.2**	**0.8**	**0.7**	0.4
	Prolonged cold events									
Δ Frequency (yr^{-1})	**−2.5**	**−1.3**	**−1.9**	**−2.8**	**−1.6**	**−1.2**	**−2.3**	**−1.2**	**−1.8**	**−1.3**
Δ Length (days)	**−2.8**	**−4.3**	**−3.8**	**−2.7**	**−2.2**	**−3.2**	**−2.6**	0.2	−0.5	0.1
Δ T_{mean} (°C)	0.1	0.2	**0.4**	**0.2**	**0.6**	**0.6**	0.1	0.1	**0.9**	0.5

TABLE 4. Changes in annual precipitation and frequency of 1-day extreme events. All Δ values are calculated as 2 × CO_2 results minus 1 × CO_2 results. Values in bold type indicate statistically significant results at the 95% confidence level (5% significance level). For basin names and locations see Fig. 1. Descriptions of the variables and methods of calculation are given in section 4, analysis methods.

	Basins									
	1	2	3	4	5	6	7	8	9	10
					Annual rainfall					
Δ Rainfall/rain day (cm)	−0.02	0.00	−0.02	−0.02	−0.02	−0.04	−0.01	**0.02**	0.02	**0.05**
Δ Rain (days yr^{-1})	−4.6	−3.2	0.9	−5.1	**−7.6**	−4.7	−2.1	**−11.1**	−9.0	−7.5
Δ Total rain (cm yr^{-1})	−3.0	−0.4	−1.4	−3.4	−5.4	−8.1	−1.9	1.1	−3.3	1.7
					Extreme wet events (P_{95})					
P_{95} Index (cm day^{-1})	0.68	0.07	0.29	0.49	1.18	1.25	0.44	0.44	0.72	1.10
Δ P_{95} (days yr^{-1})	**−3.2**	−3.2	**−2.6**	−2.4	−2.1	−1.7	−3.0	2.8	−1.1	2.3

Mearns et al. (1995) performed a similar regional modeling experiment of the continental United States for a relatively short period (3.5 yr), at lower spatial resolution (60 km), focusing entirely on temperature variability and DTR. They found increases in minimum and maximum temperatures across the domain and substantial regional differences in the sign of change of the DTR. Our study differs from Mearns et al. (1995) in that it is of much greater duration and gives a more detailed picture for a topographically and climatically complex region.

Our examination of several temperature indices indicates a potentially warmer climate in California in the future. We find potential for earlier and longer growing seasons, more frequent hot days, and more prolonged heat waves. Associated with these warming trends we find a decrease in the number of frost days, fewer cold days, and fewer, shorter, and warmer cold spells.

Observational and modeling studies have examined DTR and generally concluded that the diurnal range will decrease as mean temperatures rise in the future, based on a greater increase in diurnal minimum temperatures than maximum temperatures (Easterling et al. 1997; Gaffen and Ross 1998; Mearns et al. 1995). With the exception of Mearns et al. (1995), the previous modeling studies reporting decreased DTR were all based on global model results, but Mearns et al. (1995), a regional modeling study, reported both increased and decreased DTR depending on the region. We examined DTR in our GCM simulations and found that CCM3 also simulates decreased DTR for California with increased CO_2. Like Mearns et al. (1995), the change in DTR simulated by our RCM varies across the model domain, but in general we find a small increase in DTR due to slightly larger increases in daily maximum temperatures than for daily minimum temperatures. While RegCM2.5 and CCM3 contain very similar atmospheric physics and output temperature results at the same frequency (noon and midnight daily), RegCM2.5 has both temporal and spatial resolutions that are an order of magnitude finer than in CCM3. Therefore it is possible that these results differ from GCM studies due to the increased resolution of the RCM.

Several studies, both observational and modeling studies, imply that with a warmer climate comes an exaggerated/accelerated hydrologic cycle leading to a wetter world (Trenberth 1999; Groisman et al. 1999; McGuffie et al. 1999). In truth, changes in precipitation cannot be summed up in such a broad statement because precipitation is highly variable regionally and temporally. For example, Salinger and Griffiths (2001) found both increases and decreases in the frequency and intensity of precipitation events across New Zealand alone. Likewise, we find large differences in the responses of California's 10 hydrologic basins to a doubling of atmospheric CO_2 concentrations. The average amount of rain per year does not change significantly nor does the average amount of rain per rain day (for most basins), even though there are ~5 fewer rain days per year. In the North Coast and North Lahontan basins we find ~2.5 additional rainfall events per year that exceed the 95th-percentile event, while the remaining basins have ~2.4 *fewer* events per year exceeding the 95th percentile. Many of the precipitation results are not statistically significant due to the substantial natural variability of precipitation. This underscores the need for more, longer duration regional modeling studies of climate change. This is especially true for topographically and climatically complex regions.

7. Conclusions

We have demonstrated the utility of a regional climate model for describing potential future changes in important climate variables. Specifically, for the climatically complex region of California significant changes in extreme temperatures and precipitation events are possible in the future. These changes could have major impacts on human health, agricultural sustainability, water use and availability, and energy production and consumption. Studies such as this are necessary for the process of identifying and quantifying the impacts of climate change on a scale that is relevant and accessible at a societal level.

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