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Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios

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Abstract A hydrologic model was driven by the climate projected by 11 GCMs under two emissions scenarios (the higher emission SRES A2 and the lower emission SRES B1) to investigate whether the projected hydrologic changes by 2071–2100 have a high statistical confidence, and to determine the confidence level that the A2 and B1 emissions scenarios produce differing impacts. There are highly significant average temperature increases by 2071–2100 of 3.7°C under A2 and 2.4°C under B1; July increases are 5°C for A2 and 3°C for B1. Two high confidence hydrologic impacts are increasing winter streamflow and decreasing late spring and summer flow. Less snow at the end of winter is a confident projection, as is earlier arrival of the annual flow volume, which has important implications on California water management. The two emissions pathways show some differing impacts with high confidence: the degree of warming expected, the amount of decline in summer low flows, the shift to earlier streamflow timing, and the decline in end-of-winter snow pack, with more extreme impacts under higher emissions in all cases. This indicates that future emissions scenarios play a significant role in the degree of impacts to water resources in California.

1 Introduction

Climate change is affecting the water resources on which populations in the western US rely (e.g., Mote et al. 2005; Stewart et al. 2005; Trenberth et al. 2003), and continued anthropogenic emissions of greenhouse gases will exacerbate these effects for future decades and centuries (e.g., Dettinger et al. 2004; Hayhoe et al. 2004; Knowles and Cayan 2004; Stewart et al. 2004). Recognizing the crucial role management of water resources plays in sustaining California's economy (Draper et al. 2003), the high sensitivity of its ecosystems to climatic changes (Field et al. 1999), and the vulnerability of California's water supply to

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changes in precipitation or temperature, studies of the potential impact of climate change on California began nearly two decades ago. (Gleick 1987; Lettenmaier and Gan 1990).

The importance of this issue continues to generate considerable research using relatively coarse resolution Global Climate Models (GCMs) to drive land surface hydrology models (e.g., Brekke et al. 2004; Knowles and Cayan 2004; Maurer and Duffy 2005; Miller et al. 2003; Van Rheenen et al. 2004). Recent efforts using finer resolution regional climate models have attempted to define with more precision the spatial variability of anticipated changes in future hydroclimatology over California. (Kim et al. 2002; Kim 2005; Snyder et al. 2002). While there are many points of qualitative agreement between the wealth of studies on the topic, these studies tend to emphasize one or several selected potential outcomes, and the uncertainty in the projected impacts is not quantitatively addressed.

Quantifying the uncertainties in projections of climate change and its impacts is essential for assisting California policy-makers and water managers in adopting coherent and informed response strategies reflecting the state of scientific understanding of the likelihood of outcomes (Dettinger 2004; Kiparski and Gleick 2004). For assessing regional hydrologic impacts, one can consider four levels of uncertainty. The first three relate to the generation of regional climate information (Intergovernmental Panel on Climate Change, IPCC 2001) and consist of uncertainty in the future emissions of greenhouse gases, differing responses of GCMs to the resulting concentrations of these gases, and the uncertainty added by the downscaling technique used to translate the coarse scale GCM output to a regional spatial scale. Recent studies have also identified land use, implicit in the derived future emissions scenarios but not typically included in GCM simulations, as a potentially significant factor in regional climate (Feddema et al. 2005). This would add to the level of uncertainty of future regional climate effects represented by current GCM simulations included in this study. The fourth level of uncertainty relates to the selection and implementation of the land surface hydrology model. For regional hydrology impact studies, only recently have these differing sources of uncertainty been examined separately (e.g., Hayhoe et al. 2004; Wilby and Harris 2006; Zierl and Bugmann 2005).

Maurer and Duffy (2005) studied the projected regional impacts of rising CO_2 levels on California streamflow using GCM simulations performed between 1995 and 2002, archived as part of the Coupled Model Intercomparison Project (CMIP, Covey et al. 2003; Meehl et al. 2000). They examined only the second level of uncertainty outlined above, that is, the differing sensitivities of different GCMs under identically changing atmospheric conditions (a 1% per year CO_2 increase) to address the question of how variability in GCM responses affects the confidence with which we can expect different streamflow changes. In this study, more recent GCM simulations are used, reflecting the most recent improvements in model parameterzations and structures. In addition, the new GCM simulations are performed for many different SRES scenarios (rather than a fixed rate of increase in CO_2), which allows comparison across different potential futures, addressing both the first and second levels of uncertainty discussed above.

Taking advantage of many new GCM simulations under different emissions scenarios, the following questions are posed: (1) What are the projected hydrologic impacts of climate change on Sierra Nevada mountain hydrology, and with what confidence, relative to the variability between GCMs, are these different from the base period of 1961–1990?; (2) With what confidence are the impacts under the two scenarios considered here different at the end of the century? These questions are addressed by forcing a land surface hydrology model with the future climate projected by different GCMs, and creating an ensemble of hydrologic responses under each emissions scenario.

2 Data and methods

2.1 Study region

The area of focus for this study is California, which is depicted in Fig. 1. In particular, the analyses that follow initially included four basins, the outlets of which are shown on Fig. 1. The basins drain western slopes of the Sierra Nevada mountain range, supplying fresh water to the extensive system of dams and reservoirs serving the water demands of much of the state. All four points are at inflows to large reservoirs. Characteristics of the four points identified in Fig. 1 are in Table 1, which shows the southern two basins (basins 3 and 4) contain more high elevation areas than the northern two (basins 1 and 2), and together a range of mean basin elevations is represented. Snow plays a crucial role in the management of seasonal water storage and delivery: On average the amount of water stored as snow in the Sierra Nevada (including only those areas that ultimately drain into the Sacramento–San Joaquin River system) on April 1, about 12.4 km^3 (Hayhoe et al. 2004), is more than twice the total capacity of Lake Shasta, the largest manmade reservoir in California. Since one of the principal impacts of climate change on California water resources is on snowpack, and hydrologic changes exhibit a strong dependence on elevation (Knowles and Cayan 2004),

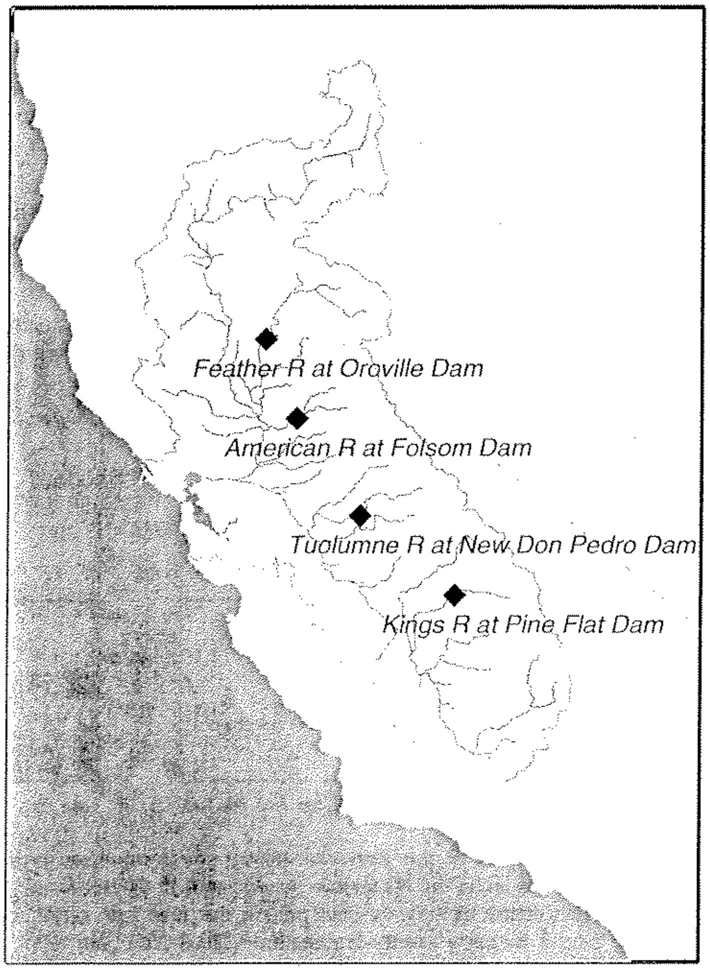

Fig. 1 Location of the outlets to the four basins included in this study. Names indicate the river and the reservoir/dam into which the river discharges

3.2 Streamflow and snow changes

The above changes in *P* and *T* produce changes in the hydrologic response of the landscape, which are reflected in the streamflow changes shown in Figs. 5 and 6. Note that Fig. 5 shows for basin 1 the ensemble mean flow changes corresponding to the GCM traces of flow in Fig. 2. For the lower elevation gauges, Fig. 5 shows high statistical confidence for the increases in December–February flows in all time periods, and the increases rise in magnitude through the century. This reflects the increasing *P* during these months under both scenarios as well as T-driven effects of increased proportions of *P* falling as rain instead of snow, and increased snow melt. The T-driven effects dominate, and more so as *T* increases continue, with changes in December–February *P* being 15–30% of the percent change in December–February flow, with the lower values toward the end of the twenty-first century. The increases in winter flows are markedly greater for the A2 scenario than B1, especially for 2071–2100. For A2, April–September flows decline, and the magnitude of this drop in flow increases through the twenty-first century. For B1 the same pattern is evident, but by 2071–2100 the declines in streamflow are less severe than under A2. Under the A2 scenario the increases in winter flow more than offset the declines in summer, producing a small (but low confidence) increase in annual flow for basins. The B1 scenario shows a similar effect for 2011–2040 with an increase in annual flow of 7–8% (with higher confidence of 67–90%); by 2071–2100 the B1 scenario shows a slight but low confidence decline in annual flow.

For the southern two basins at higher elevation, Fig. 6 illustrates the same pattern of changes for the southern basins. These show increased flows through April despite decreasing *P* in March and April. This is in contrast to the lower elevation northern basins,

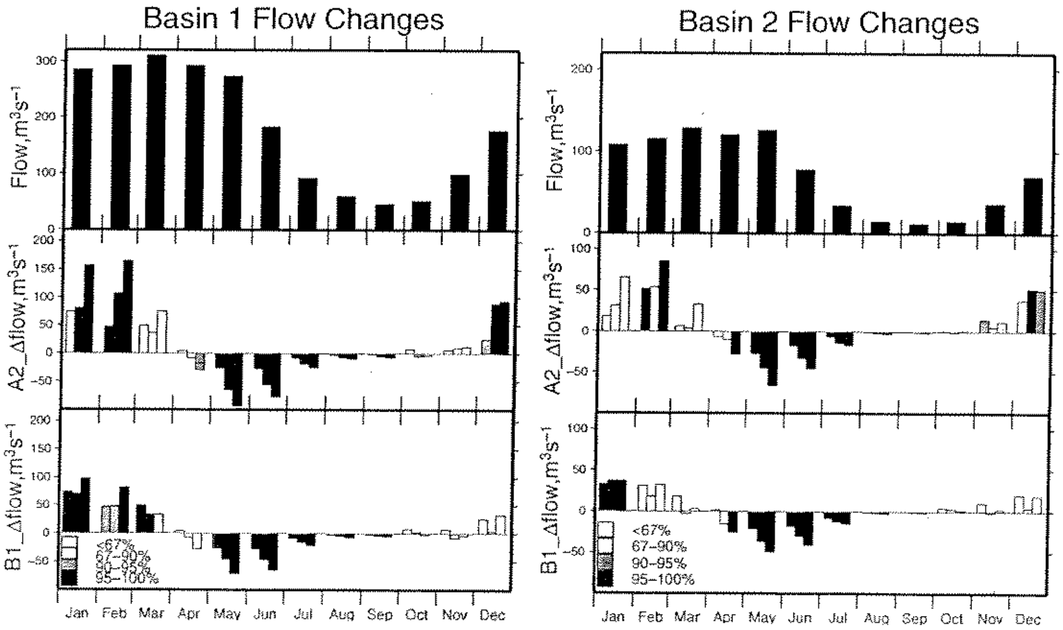

Fig. 5 Similar to Fig. 3, this shows in the *top panel* the mean monthly flow for Basins 1 and 2, and the projected changes under the A2 (*center panels*) and B1 (*lower panels*) emission scenarios. *Shading* indicates statistical confidence. In the *lower two panels*, the three bars within each month indicate changes relative to the base period for early twenty-first century (2011–2040; *left bar*), mid–century (2041–2070; *center bar*) and end of century (2071–2100; *right bar*)

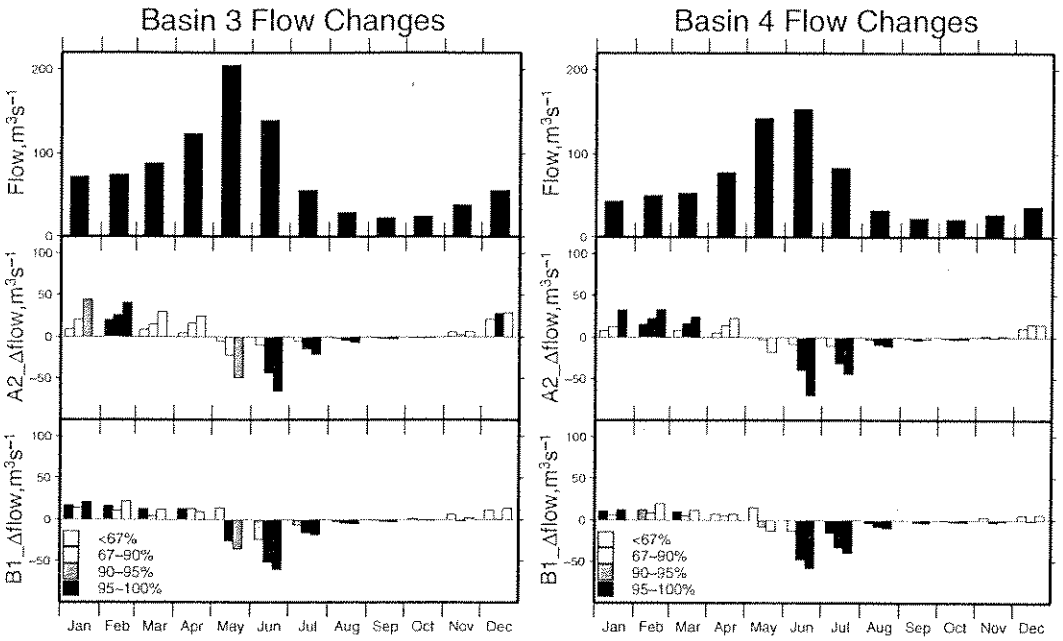

Fig. 6 Same as Fig. 5 but for Basins 3 and 4

where flow increases continue only through March, with smaller declines and even some increasing *P*. This illustrates the interplay between *T* and *P* changes, where at higher elevation increases in December–February *P* can be stored as snow, later to augment flow. The statistically significant declines in late spring to early summer streamflow for 2071–2100 are limited to a shorter duration compared to the northern basins. Under the A2 scenario, the winter increase is offset by the late season decrease in flow, and the annual volume changes little. Under B1, the same pattern as in the north is seen, though by 2071–2100 the decreases in annual flow volume achieve higher confidence, especially basin 4.

The A2 and B1 emissions scenarios do not produce streamflows differing with a high degree of confidence, as shown in Table 4. The drops in May–August flow display the highest confidence that A2 and B1 result in different flow responses, with A2 showing sharper declines. The confidence in the difference between the scenarios is lower for the

Table 4 Confidence that the mean flow for the A2 and B1 scenarios differ between 2071–2100 and the 1961–1990 base period

Month	Basin 1 (%)	Basin 2 (%)	Basin 3 (%)	Basin 4 (%)
Jan	60	30	56	63
Feb	48	52	48	48
Mar	56	60	44	49
Apr	44	**70**	48	56
May	**78**	**88**	35	25
Jun	**90**	**78**	63	**68**
Jul	**73**	**85**	60	**76**
Aug	**70**	**81**	57	**72**
Sep	63	55	28	44
Oct	25	18	0	30
Nov	44	62	60	47
Dec	44	52	20	10
Annual	15	30	10	0

Basin numbering is as in Table 1. Values larger than 67% are bold.

Table 5 Mean April 1 SWE and percent change

April 1 SWE		SRESA2			SRESB1		
Basin	1961–1990 mean (mm)	2011–2040 Δ (%)	2041–2070 Δ (%)	2071–2100 Δ (%)	2011–2040 Δ (%)	2041–2070 Δ (%)	2071–2100 Δ (%)
1	114	**−38**	**−59**	**−80**	**−32**	**−46**	**−69**
2	121	**−29**	**−50**	**−71**	**−27**	**−38**	**−59**
3	305	−7	**−24**	**−39**	−7	**−22**	**−35**
4	360	−9	**−27**	**−43**	−8	**−24**	**−36**

Bold values indicate changes that exceed 95% confidence.

higher elevation southern basins showing declining sensitivity to the differences between A2 and B1 for the low flow period.

Table 5 summarizes the change in April 1 SWE for each basin for each time period. April 1 snowpack is a widely used indicator of the water available as summer supply in the western US (e.g., Hamlet and Lettenmaier 1999, Knowles and Cayan 2004); a decrease indicates either earlier melt and/or reduced winter snow accumulation. There is a clear pattern of lower snow loss for the southern, higher elevation basins, attributable to the fact that rising temperatures at higher elevations are less likely to bring temperatures above freezing and cause snow melt. Although there is significantly greater warming under A2, December–February P increases more dramatically for A2 than under B1 which results in small differences in April 1 SWE losses under the different emission scenarios through the early twenty-first century. By the mid–late twenty-first century, the T changes have become dominant, and B1 shows 11–13% less April 1 SWE loss compared to A2 at the lower elevation, northern basins. For the southern basins the difference in April 1 SWE loss is lower at 2–7%, showing that even with the projected T increases a substantial portion of the basins remain above the freezing level, thus T impacts on snow are lessened. All snow losses by mid-century are high confidence. The confidence level that the April 1 SWE loss projected under the two scenarios differs exceeds 80% for the lower elevation, northern basins, showing that while the impacts on April 1 SWE are high in all basins, the moderate elevation mountain basins will experience distinctly different snow impacts depending on future emissions pathways.

The earlier melt due to rising temperatures produces a shift in the date of the centroid of the annual flow volume, which is calculated using the center-of-mass approach of Stewart et al. (2004) and is shown in Table 6. Due to the compounding effects of increasing winter P, decreasing spring P, more winter P falling as rain instead of snow and earlier snow melt

Table 6 Date of the centroid of the annual flow volume, and the shift in days

Flow centroid		SRESA2			SRESB1		
Basin	1961–1990 mean (days)	2011–2040 Δ (days)	2041–2070 Δ (days)	2071–2100 Δ (days)	2011–2040 Δ (days)	2041–2070 Δ (days)	2071–2100 Δ (days)
1	78	**−14**	**−18**	**−23**	**−10**	**−11**	**−17**
2	81	**−19**	**−23**	**−31**	**−17**	**−20**	**−26**
3	119	**−9**	**−20**	**−33**	**−10**	**−14**	**−23**
4	137	**−9**	**−21**	**−36**	**−8**	**−16**	**−24**

Mean is in day of year (January 1=1). Bold values indicate changes that exceed 95% confidence.

under higher *T*, there is a high degree of confidence that the shift is statistically significant for all basins and periods. Given the modest shift in the centroid of annual *P* (see Section 3.1), the shift in the centroid of the annual flow volume is predominantly due to *T* changes driving a greater proportion of rain and earlier snow melt. The continuing shift to earlier arrival of runoff later in the twenty-first century is robust for all basins, showing the effect of increasing *T* changes. Early in the twenty-first century the timing shift is highly significant but the differences between the A2 and B1 scenarios is less so, with confidence that the impacts under the A2 and B1 scenarios differ exceeding 75% only for the lower elevation basins. By 2041–2070, the shift for the B1 and A2 scenarios is different at the 90% confidence level for all but the highest elevation basin, basin 4. By 2071–2100 the confidence that the response differs under the two scenarios exceeds 90% for all basins, with the greatest difference in impacts seen at the higher elevation basins, showing that once the *T* change is great enough to affect the high elevation basins, impacts are more dramatic than for moderate elevation basins.

4 Conclusions

For four basins in the Sierra Nevada in California, the simulated hydrologic impacts of future climate projected by 11 GCMs forced under two SRES emissions scenarios, a higher emission A2 and lower emission B1, were examined for statistical significance. While these scenarios do not represent worst and best case of possible emissions scenarios, of the selected SRES scenarios available for this study they do represent the generally bounding scenarios for twenty-first century CO_2 emissions. With this structure, this study addresses only uncertainty related to inter-GCM and inter-emissions scenario variability, not uncertainty due to the downscaling technique or the hydrology model transforming downscaled climate to streamflow. The two questions posed for this study are whether (and when) the projected hydrologic impacts have high statistical confidence (relative to the variability among GCMs), and whether the impacts under the two scenarios differs with high confidence.

Temperature (*T*) shows highly significant increases over 1961–1990 levels, even early in the twenty-first century. By 2071–2100 T rises by an average of 3.7°C under A2 and 2.4°C under B1, with July temperatures rising most dramatically by 5°C for A2 and 3°C for B1. The difference between the *T* increases, between 2071–2100 and 1961–1990, under A2 and B1 are highly significant. Thus it can be confidently stated that the emissions pathway we follow determines the future temperature experienced in the study region; alternatively, the choice of policies affecting future global emissions has a discernable impact in this region.

The same cannot be claimed so broadly for precipitation (*P*). Increases in winter *P* and decreases in spring *P* are projected, both with generally higher magnitudes under A2 than B1, especially by 2071–2100. While annual *P* does not generally differ between the emissions scenarios, decreases in April–May *P* are significantly greater for A2 than B1.

For streamflow at the basin outlets, flow increases for December–March, and through April for higher elevation basins. Flows decline for April–September in the lower elevation basins, and May–October at higher elevations. Increases in winter and decreases in summer flow are both of greater magnitude under A2 than B1. The highest confidence in the differing response under A2 and B1 are for May–August declines in streamflow, where the decreases are sharper under A2 than B1.

By 2071–2100, the 36–80% losses in April 1 snow water equivalent (SWE) are highly significant for all basins, with greater losses at lower elevations. Greater losses under A2 than B1 are demonstrated with high confidence for lower elevation basins only, showing the changing sensitivity to emissions level with elevation.

The combined effects of changes in *P*, *T* and SWE result in an earlier arrival of the annual flow volume by as much as 36 days by 2071–2100. For all basins, the difference in this shift for B1 emissions scenario is significantly less than for A2 by the end of the century.

In summary, as temperatures rise through the twenty-first century we can expect with high confidence an increase in winter streamflow from the Sierra Nevada, due primarily to temperature-driven effects of increasing proportion of rain versus snow and earlier snow melt, and secondarily to increasing winter *P*. We can also expect to experience a decrease in late spring and summer flow, which has important implications for California water management. We can confidently expect to have less water stored as snow at the end of winter, and we will expect an earlier arrival of the water, with implications on how reservoirs are managed. The emissions pathway, whether A2 or B1, shows some important differences in impacts, especially on the degree of warming expected, the decline in summer low flows, water stored as snow pack, and the shift to earlier streamflow timing, indicating that our emissions future determines to some extent the degree of impacts to water resources in California.

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