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Uncertainty in hydrologic impacts of climate change in the Sierra Nevada Mountains, 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 SRESA2 and the lower emission SRESB1) 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 in streamflow timing for higher elevation basins, 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 U.S. 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 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 Rheenan 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. 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: for example Hayhoe et al. (2004) examined two GCMs and two emissions scenarios over California; Zierl and Bugmann (2005) evaluated hydrologic responses with four SRES scenarios using one GCM, and four GCMs under one emissions scenario.

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 Figure 1. In particular, the analyses that follow initially included four basins, the outlets of which are shown on Figure 1

Figure 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 Figure 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 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), the selection of basins included in this study is designed to illuminate these differing responses.

Table 1

2.2 Global Climate Models

Many international modeling groups are completing simulations of present climate and future climate under selected IPCC SRES scenarios in preparation for the IPCC 4th Assessment Report (AR4). (Meehl et al., 2005) For this study, simulations are used from the 11 GCMs that by March 1, 2005 had completed at least one simulation each of the 20th century climate and future climate (through 2100) using emissions scenarios SRES A2 and B1. While A2 does not represent the highest CO_2 emissions (at least through 2100) of the SRES scenarios (IPCC, 2001), it is the highest emission scenario being archived as part of CMIP. As such, although it is by no means a “worst case,” it does represent the higher emission case in this study. B1 assumes an increasing reliance on clean and resource-efficient technologies, and represents the best case of the SRES scenarios. (IPCC, 2001)

The GCMs included in this study are shown in Table 2. For each GCM, and each period (20^{th} century, scenarios A2, B1) monthly precipitation (P) and temperature (T) data were obtained from the IPCC AR4 data archive hosted by the Program for Climate Model Diagnosis and Intercomparison. Where a GCM has archived more than one simulation under a particular scenario, the ensemble average is used, so as not to bias the population of GCMs toward any specific model. All GCMs are interpolated onto a common 2° latitude-longitude grid, approximately equal to the spatial scale of the finest GCMs included in this study, to standardize the analysis that follows.

Table 2

2.2.1 GCM bias correction and spatial downscaling

While large scale patterns of precipitation and temperature simulated by state-of-the-art GCMs can be realistic, even the best models display biases on regional scales that are large enough to confound studies of the hydrologic impacts of climate change. To cope with this, many different techniques have been employed to process the raw GCM output to retain the large scale signal of the evolving climate simulated by the GCM while reproducing historical climate patterns on the landscape at local scales, an essential characteristic for meaningful hydrologic analysis (Wood et al., 2004). One method used in many studies is to use a shift or scaling factor derived by comparing a climate model's future precipitation or temperature to its climatology, and to apply this shift to a historical record (e.g., Miller et al., 2003; Lettenmaier and Gan, 1990). While this method effectively removes the bias of the mean GCM climatology from the future climate, it does not address the potential bias in the variability of the climate model and constrains inter-annual variability to be constant.

For this study, we employ a bias correction technique originally developed by Wood et al. (2002) for using global model forecast output for long-range streamflow forecasting. This technique was later adapted for use in studies examining the hydrologic impacts of climate change (Hayhoe et al., 2004; Maurer and Duffy, 2005; Payne et al., 2004; Van Rheenan et al., 2004). This is an empirical statistical technique that maps precipitation and temperature during a historical period (1950-1999 for this study) from the GCM to the concurrent historical record. The historical data used in this study is gridded National Climatic Data Center Cooperative Observer station data, developed as described in Maurer et al. (2002), and aggregated up to a 2° latitude-longitude spatial resolution. For P and T, cumulative distribution functions are built for each of 12 months for each of the 2° grid cells for both the gridded observations and each GCM for the climatological period. GCM quantiles are then mapped onto the climatological CDF for the entire simulation period. For example, if for one grid point the GCM P value in January of 2050 is equal to the median GCM value for January for 1950-1999, it is transformed to the median value for the gridded January observations for 1950-1999. For T, the linear trend is removed prior to this bias correction and replaced afterward, to avoid increasing sampling at the tails of the CDF as temperatures rise. Thus, the probability distribution of observations is reproduced by the bias corrected climate model data for the overlapping climatological period, while both the mean and variability of future climate can evolve according to GCM projections.

Climate model output, which at 200-500 km is at too large a scale for basin scale hydrologic analysis, requires spatial downscaling prior to its use in a hydrology model. This can be done with dynamical or statistical methods (see for example Benestad, 2001; Mearns et al., 2001). The main disadvantage of dynamic downscaling is the computational effort involved, which renders its use impractical for extended transient simulations of multiple emissions scenarios, as used in this study. The method used in this study is that applied by Wood et al. (2002), which for each month interpolates the bias corrected GCM anomalies, expressed as a ratio (for precipitation) and shift (for temperature) relative to the climatological period at each 2° GCM grid cell to the centers of 1/8 degree hydrologic model grid cells over California. These factors are then applied to the 1/8 degree gridded precipitation and temperature. The combined bias correction/spatial downscaling method used in this study has been shown to compare favorably to different statistical and dynamic downscaling techniques (Wood et al., 2004) in the context of hydrologic impact studies.

2.3 Hydrologic Model Simulations

The hydrologic model used in this study is the variable infiltration capacity (VIC) model (Liang et al. 1994; 1996). VIC is a macroscale, distributed, physically-based hydrologic model that balances both surface energy and water over a grid mesh, typically at resolutions ranging from a fraction of a degree to several degrees latitude by longitude. One distinguishing characteristic of the VIC model is its use of a "mosaic" scheme, allowing a statistical representation of the sub-grid scale spatial variability in topography and vegetation/land cover, which is especially important when simulating the accumulation and ablation of snow in more complex terrain. To account for subgrid variability in infiltration, the VIC model uses a scheme based on the work by Zhao et al. (1980). The VIC model also features a nonlinear mechanism for simulating slow (baseflow) runoff response, and explicit treatment of vegetation effects on the surface energy balance. The resulting runoff at each grid cell is routed through a defined river system using the algorithm developed by Lohmann et al. (1996). The VIC model has been successfully applied in many settings, from global to river basin scale (e.g., Abdulla et al., 1996; Maurer et al. 2001, 2002; Nijssen et al., 1997, 2001), as well as in several studies of hydrologic impacts of climate change (Christensen et al, 2004; Hayhoe et al., 2004; Maurer and Duffy, 2005; Payne et al., 2004; Wood et al., 2004). For this study, the model was run at a 1/8-degree resolution (measuring about 150 km^2 per grid cell) over the Sacramento-San Joaquin river system, using the identical parameterization as Van Rheenan et al. (2004).

2.4 Assessing uncertainty in hydrologic impact projections

Following the approach of Maurer and Duffy (2005), results for each impact, in this case streamflow and snowpack, for all GCMs are assembled for each emissions scenario. For each variable, the mean monthly value for each GCM for each of three defined periods is calculated, and these values for each GCM are combined by variable and period into ensembles. These ensembles of hydrologic variables are statistically analyzed using 2-sided t-tests to determine the confidence level for the change from the climatological period (1961-1990). In addition, the confidence with which one can claim that the two scenarios give different results is determined.

3. Results and Discussion

For a domain including all four of the study basins the hydrologic model produced complete estimates of the water budget using each GCM. These were then summarized for four periods: the base period 1961-1990, 2011-2040, 2041-2070, and 2071-2100. For one basin, under the A2 scenario, the results for the latter two periods are plotted in Figure 2. This shows that winter P increases but is quite variable between the models, while the T increases appear more consistent. In general the impact on flow of these climatic changes is that winter flows increase and late spring and early summer flows decrease, with greater disagreement between models during the transition between the two. Declining snow water equivalent (SWE) is clear, and is more severe later in the century as temperatures continue to rise. Figure 2

3.1 Precipitation and temperature changes

To verify statistically the observations above related to T and P, and use both emissions scenarios, Tables 3 and 4 are shown. Note that the 90% and 95% confidence thresholds highlighted in the Tables are comparable to the National Assessment Synthesis Team (2000) classification of "very likely or very probable" impacts as those with confidence >90%. Since the changes in the P and T forcing were found to be remarkably consistent between basins, only the northern and southernmost basins are included in this section. Each Table shows for each month and for the annual total the mean of the 1961-1990 base period and the change to each of the three future periods. Annual average P increases significantly by about 10% in the North early in the 21st century, with most of the increase in December-February. A significant decline in April-June P appears later in the century, and the increase in Winter P persists. Table 4 shows a similar pattern toward the South, though with sharper declines in April-June P than in the North. While not shown in the tables, the T projections in the North and South are very close and are highly significant, even as early as 2011-2040. By the end of the 21st century, average annual T rises by 3.6-3.8 °C for the A2 scenario, and 2.3-2.4 °C for B1, with the greatest warming being in July with 3.0-3.1 °C for the B1 scenario and 5.0-5.1 °C for A2. While these changes are broader scale, showing high consistency between the North and South, the differing characters of the basins produces different hydrologic responses.

Table 3

Table 4

To assess the separation of the future climate under the two SRES scenarios, Table 5 shows the statistical confidence with which the 2071-2100 T and P differ for the two scenarios. While both scenarios show highly significant changes in T by the end of the century, Table 5 also shows that, with the exception of March and April, the temperature rises are smaller for B1 as compared to A2 with high statistical confidence. For March and April, the confidence that the future T under the two scenarios is different is below 90% but is higher for the higher elevation basins, suggesting that during these months T-driven effects under the two scenarios may differentiate more by elevation. Table 5

For the annual average P the two scenarios produce statistically indistinguishable futures. Even at the monthly scale the differences in projected P for 2071-2100 under the two scenarios are not generally different with a high degree of confidence. The exception is March and April, where the decline in P projected under the A2 scenario is significantly greater than under B1, exceeding 90% confidence for the higher elevation basins.

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 Tables 6 and 7. For the lower elevation gauges, Table 6 shows high statistical confidence for the increases in December-March flows in all time periods. This reflects the increasing P during these months under both scenarios. The increases in December-March flows are markedly greater for the A2 scenario than B1. For A2, May-September flows decline, and both the Table 6 Table 7 magnitude and the statistical confidence increase through the 21st century, since these changes are largely T-driven. For B1 the same pattern is evident, but is limited to May-August, and by the end of the century the declines in streamflow are uniformly less severe than under A2 and generally of lower confidence. Decreased summer flows in 2071-2100 have more limited duration under the B1 scenario than under A2, with 4 consecutive months with flow declines at >95% confidence, compared to 5 months for A2. The increases in winter flow more than offset the declines in summer, producing an increase in annual flow for both basins, with the increase being lower for B1 and for the higher elevation basin.

For the southern 2 basins at higher elevation, Table 7 continues the same pattern of annual flow changes, where annual flow increases are lower in magnitude for B1, and are lower in magnitude for the higher elevation basin. The southern basins show increased flows through April-May despite decreasing P. This is in contrast to the lower elevation Northern basins, where flow increases continue only through March-April, 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 streamflow for 2071-2100, are limited to 3 months in duration, in contrast to 4 months for each of the Northern basins.

The two scenarios do not produce streamflows differing with a high degree of confidence, as shown in Table 8. The declines in August-September flow display the Table 8 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 higher elevation basins showing declining sensitivity to the differences between A2 and B1 for the low flow period.

Table 9 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 U.S. (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, showing 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 greater April 1 SWE losses under the lower emission B1 scenario though mid-century. By the end of the 21st century, the T changes have become dominant, and B1 shows 8-10% less April 1 SWE loss compared to A2, and there is high confidence in all projected losses. The confidence level that the April 1 SWE loss projected under the two scenarios differs is below 60% (using a 2-sided t-test) for all basins, showing that although the impacts on April 1 SWE are high, the scenarios do not show a statistically significant difference by 2071-2100. Though not shown, the projected declines in December-February monthly average SWE are 30-45% for B1 and 50-60% for A2 for the lower elevation basins, and for this measure the difference between the changes under A2 and B1 generally differ with higher confidence levels of over 80%.

Table 9

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 10. Due to the compounding effects of increasing Winter P, decreasing Spring P, more P falling as rain and earlier snow melt under higher T, the shift in the timing of the annual hydrograph is highly confident for all basins and periods. The continuing shift to earlier arrival of runoff later in the 21st century is robust for all basins. For the lower elevation basins, the difference between the shift for the B1 and A2 scenarios for 2071-2100 is only 4 days, hence the confidence that the response differs under the two scenarios is low (<60%). In contrast, for the higher elevation basins the difference is 11-12 days, and there is greater than 90% confidence that the impact under A2 is more dramatic than under B1.

Table 10

4. Conclusions

For four basins in the Sierra Nevada Mountains 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 21st century emissions. With this structure, this study addresses only uncertainty related to inter-GCM and inter-emissions scenario variability, not uncertainty due to the hydrology model transforming 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 between 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 21st 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. This indicates it can be confidently stated that the emissions pathway we follow significantly determines the future temperature experienced in the study region.

The same cannot be claimed so broadly for precipitation (P). Increases in Winter P and smaller decreases in Spring P are projected, with higher confidence under A2 than B1, especially by 2071-2100. While annual P does not 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-May for higher elevation basins. Flows decline for May-September in the lower elevation basins, and June-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 August-September declines in streamflow, where the decreases are sharper under A2 than B1.

By 2071-2100, the 30-69% losses in April 1 snow water equivalent (SWE) are highly significant for all basins, with greater losses at lower elevations. The approximately 8-10% greater losses under A2 than B1 is not high confidence, showing the variability in results for different GCMs is larger for this variable.

The combined effects of changes in P, T and SWE result in an earlier arrival of the annual flow volume by as much as 40 days by 2071-2100. For the high elevation basins, the difference in this shift for B1 is significantly less than for A2.

In summary, as temperatures rise through the 21st century we can expect with high confidence an increase in winter streamflow from the Sierra Nevada, due at least partly to increasing winter P, and 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, and the shift in streamflow timing for higher elevation basins, indicating that our emissions future determines to some extent the degree of impacts to water resources in California.

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Table 1 - Locations and characteristics of the four basins in this study.

Characteristic	Outlet point and basin characteristics			
Site Name	1. Feather R at Oroville	2. American R at Folsom Dam	3. Tuolumne at New Don Pedro Res	4. Kings R. at Pine Flat Dam
Latitude	39.522	38.683	37.666	36.831
Longitude	-121.547	-121.183	-120.441	-119.335
Drainage Area, km^2	9350	4850	3970	4000
Mean Basin Elevation, m	1553	1335	1755	2196
Max Basin Elevation, m	2655	3009	3802	4086
Min Basin Elevation, m	49	50	62	183

Table 2 - GCMs included in this study.

Modeling Group, Country	IPCC Model I.D.	Abbrev.	Primary Reference
Météo-France / Centre National de Recherches Météorologiques, France	CNRM-CM3	cnrm	Salas-Mélia et al., 2005
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	csiro	Gordon, H.B. et al, 2002
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	gfdl	Delworth et al., 2005
NASA / Goddard Institute for Space Studies, USA	GISS-ER	giss	Russell et al., 1995, 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	inmcm	Diansky and Volodin, 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	ipsl	IPSL, 2005
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2(medres)	miroc	K-1 model developers, 2004
Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	mpi	Jungclaus et al.., 2005
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	mri	Yukimoto et al., 2001
National Center for Atmospheric Research, USA	PCM	pcm	Washington et al., 2000
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3	hadcm3	Gordon, C. et al., 2002

Table 3 - P summary statistics for the Basin 1 Feather River at Oroville. Values in italics are significantly different from the 1961-1990 mean at a 90% confidence level, based on a 2-sided t-test for differences in the mean. Bold italics differ with 95% confidence.

PRECIPITATION		SRESA2			SRESB1		
Month	1961-1990 Mean, mm/d	2011-2040 Δ, mm/d	2041-2070 Δ, mm/d	2071-2100 Δ, mm/d	2011-2040 Δ, mm/d	2041-2070 Δ, mm/d	2071-2100 Δ, mm/d
Jan	6.7	***1.0***	1.7	***1.8***	***1.2***	0.3	*1.1*
Feb	5.6	*1.2*	0.7	***1.5***	0.4	*1.0*	0.9
Mar	4.1	0.2	-0.2	0.3	0.2	0.2	-0.1
Apr	2.4	0.0	-0.1	***-0.5***	-0.2	*-0.3*	-0.1
May	1.6	-0.2	***-0.4***	***-0.6***	-0.2	-0.1	-0.2
Jun	0.8	0.0	***-0.2***	***-0.3***	0.0	-0.1	*-0.2*
Jul	0.2	0.0	0.0	0.0	0.1	0.1	0.1
Aug	0.3	0.0	0.0	0.0	0.2	0.2	0.2
Sep	0.6	0.0	-0.1	0.0	0.2	0.3	0.3
Oct	1.9	0.1	0.2	0.2	0.7	0.6	0.6
Nov	4.3	*0.6*	0.6	0.5	0.8	0.4	0.6
Dec	5.8	1.1	***1.7***	1.2	0.8	0.3	*0.7*
Annual	2.8	***0.3***	0.3	0.3	***0.3***	0.2	***0.3***

Table 4 - Same as Table 3, but for Basin 4. Kings R at Pine Flat Dam.

PRECIPITATION		SRESA2			SRESB1		
Month	1961-1990 Mean, mm/d	2011-2040 Δ, mm/d	2041-2070 Δ, mm/d	2071-2100 Δ, mm/d	2011-2040 Δ, mm/d	2041-2070 Δ, mm/d	2071-2100 Δ, mm/d
Jan	6.2	***1.0***	*2.3*	*1.6*	*1.1*	0.1	0.8
Feb	5.5	***1.5***	0.6	0.8	***0.9***	0.8	0.7
Mar	4.6	0.0	-0.8	-0.6	-0.3	-0.2	-0.6
Apr	2.9	-0.3	-0.5	***-1.2***	*-0.5*	***-0.6***	-0.5
May	1.6	-0.3	***-0.5***	***-0.8***	-0.2	-0.2	***-0.4***
Jun	0.7	0.0	***-0.2***	***-0.2***	0.0	-0.1	*-0.2*
Jul	0.4	0.0	0.0	0.1	0.1	0.1	***0.2***
Aug	0.3	0.0	0.1	***0.2***	0.1	***0.2***	***0.2***
Sep	1.1	0.1	0.0	0.3	0.2	0.4	0.3
Oct	1.3	0.0	0.1	0.1	0.2	0.1	0.3
Nov	3.8	0.4	-0.1	-0.1	0.6	0.1	0.4
Dec	5.3	1.1	1.2	0.8	0.7	0.1	0.1
Annual	2.8	0.3	0.2	0.1	0.3	0.0	0.1

Table 5 - Confidence that the A2 and B1 mean P and T differ for 2071-2100. Confidence is determined with a 2-sided t-test for differences in mean. Basin numbering is as in Table 1.

	Precipitation				Temperature			
Month	Basin 1	Basin 2	Basin 3	Basin 4	Basin 1	Basin 2	Basin 3	Basin 4
Jan	50%	48%	51%	54%	97%	98%	98%	97%
Feb	51%	34%	20%	6%	95%	94%	94%	93%
Mar	59%	37%	17%	4%	59%	63%	70%	71%
Apr	83%	89%	93%	94%	76%	81%	84%	86%
May	90%	90%	91%	90%	94%	96%	97%	97%
Jun	60%	52%	54%	50%	96%	96%	96%	95%
Jul	70%	72%	69%	66%	96%	94%	94%	93%
Aug	57%	35%	20%	17%	99%	99%	98%	98%
Sep	67%	54%	34%	4%	100%	100%	100%	99%
Oct	54%	56%	57%	58%	99%	99%	99%	99%
Nov	11%	34%	51%	58%	98%	98%	98%	97%
Dec	45%	50%	54%	55%	98%	98%	98%	98%
Annual	6%	2%	3%	8%	100%	100%	100%	100%

Table 6 - Monthly and annual mean flow and percent change from the mean for the North (lower elevation) two gauges. Bold and italics signify the same confidence as for Table 2. Basin numbering is as in Table 1.

BASIN 1		SRESA2			SRESB1		
Month	1961-1990 Mean, m^3/s	2011-2040 Δ, %	2041-2070 Δ, %	2071-2100 Δ, %	2011-2040 Δ, %	2041-2070 Δ, %	2071-2100 Δ, %
Jan	258	***49%***	***83%***	***88%***	***55%***	***40%***	***62%***
Feb	312	***39%***	***47%***	***66%***	***29%***	***37%***	***48%***
Mar	302	***23%***	*18%*	***30%***	***22%***	***17%***	***18%***
Apr	299	7%	2%	-6%	3%	-1%	-4%
May	269	-5%	*-14%*	***-28%***	-8%	***-15%***	***-20%***
Jun	182	-8%	***-23%***	***-38%***	***-15%***	***-20%***	***-29%***
Jul	92	-5%	***-16%***	***-25%***	-8%	***-13%***	***-15%***
Aug	60	-2%	***-10%***	***-15%***	-3%	*-6%*	***-8%***
Sep	46	-1%	***-8%***	***-11%***	5%	4%	5%
Oct	50	14%	20%	23%	*60%*	61%	49%
Nov	100	***25%***	30%	22%	*34%*	24%	*35%*
Dec	189	***46%***	***53%***	***56%***	***41%***	*32%*	***40%***
Annual	179	***19%***	21%	*21%*	***18%***	*13%*	***17%***
BASIN 2		SRESA2			SRESB1		
Jan	96	***81%***	*140%*	***129%***	***81%***	***59%***	***87%***
Feb	127	***62%***	***70%***	***86%***	***46%***	***49%***	***65%***
Mar	126	***26%***	7%	32%	*23%*	9%	14%
Apr	125	12%	-2%	*-20%*	3%	***-10%***	***-11%***
May	124	-11%	*-23%*	***-44%***	***-13%***	*-26%*	***-32%***
Jun	80	-12%	***-31%***	***-58%***	***-22%***	***-29%***	***-44%***
Jul	35	-12%	***-31%***	***-45%***	-24%	-28%	***-34%***
Aug	15	-2%	*-13%*	***-20%***	-5%	-6%	-10%
Sep	12	1%	-7%	***-10%***	9%	12%	11%
Oct	14	34%	57%	*65%*	***118%***	123%	100%
Nov	33	***75%***	***80%***	55%	***79%***	47%	***82%***
Dec	73	***93%***	***102%***	*96%*	***76%***	*57%*	***55%***
Annual	71	***32%***	31%	26%	*26%*	14%	19%

Table 7 - Same as for Table 6, but for the South two gauges at higher elevation.

BASIN 3		SRESA2			SRESB1		
Month	1961-1990 Mean, m^3/s	2011-2040 Δ, %	2041-2070 Δ, %	2071-2100 Δ, %	2011-2040 Δ, %	2041-2070 Δ, %	2071-2100 Δ, %
Jan	67	***62%***	*107%*	***104%***	***57%***	***40%***	***62%***
Feb	76	***54%***	***68%***	***79%***	***44%***	***41%***	***61%***
Mar	89	***29%***	26%	***53%***	***27%***	*20%*	***35%***
Apr	121	***22%***	*32%*	***27%***	***27%***	***28%***	***28%***
May	198	13%	-1%	-17%	12%	-7%	-8%
Jun	148	-7%	*-25%*	***-48%***	***-20%***	***-32%***	***-37%***
Jul	57	3%	-16%	***-36%***	-10%	***-23%***	***-26%***
Aug	29	0%	-13%	***-23%***	-5%	*-10%*	***-14%***
Sep	23	1%	-7%	***-9%***	5%	7%	0%
Oct	23	4%	0%	9%	15%	11%	15%
Nov	37	***30%***	23%	26%	***35%***	15%	***38%***
Dec	57	*65%*	*66%*	*74%*	***50%***	32%	***40%***
Annual	77	*22%*	19%	14%	*17%*	6%	11%
BASIN 4		SRESA2			SRESB1		
Jan	41	***63%***	*104%*	***116%***	***57%***	***37%***	***61%***
Feb	49	***66%***	***88%***	***105%***	***54%***	***53%***	***83%***
Mar	54	***38%***	***45%***	***66%***	***35%***	***28%***	***50%***
Apr	80	***25%***	*38%*	***37%***	***30%***	***27%***	***34%***
May	140	*21%*	12%	-2%	*20%*	4%	3%
Jun	154	1%	-16%	***-44%***	-12%	***-28%***	***-32%***
Jul	84	-3%	*-29%*	***-52%***	*-20%*	***-35%***	***-42%***
Aug	32	3%	-19%	***-34%***	-10%	-17%	***-24%***
Sep	23	3%	-7%	-4%	14%	17%	-2%
Oct	21	-1%	-7%	-6%	3%	2%	0%
Nov	27	*21%*	4%	7%	*23%*	2%	19%
Dec	37	*60%*	60%	65%	*40%*	29%	*33%*
Annual	62	21%	16%	8%	14%	3%	6%

Table 8 - Confidence that the mean flow for the A2 and B1 scenarios differ for 2071-2100. Confidence is determined with a 2-sided t-test for differences in mean. Basin numbering is as in Table 1.

Month	Basin 1	Basin 2	Basin 3	Basin 4
Jan	68%	59%	71%	77%
Feb	60%	43%	45%	42%
Mar	64%	53%	58%	46%
Apr	18%	44%	5%	9%
May	59%	63%	47%	23%
Jun	72%	76%	63%	60%
Jul	78%	61%	60%	55%
Aug	85%	83%	72%	67%
Sep	91%	87%	70%	12%
Oct	50%	39%	29%	34%
Nov	35%	40%	38%	52%
Dec	46%	61%	60%	56%
Annual	28%	25%	14%	8%

Table 9 - Mean April 1 SWE and percent change. Bold and Italics are used identically to Table 3.

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	109	***-21%***	***-42%***	***-69%***	***-29%***	***-42%***	***-59%***
2	119	***-15%***	***-33%***	***-63%***	***-24%***	***-33%***	***-53%***
3	302	0%	-15%	***-38%***	-7%	***-20%***	***-30%***
4	354	0%	-16%	***-40%***	-8%	***-22%***	***-32%***

Table 10 - Date of the centroid of the annual flow volume, and the shift in days. Mean is in day of year (January 1=1).

Flow Centroid		SRESA2			SRESB1		
Basin	1961-1990 Mean, day	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	***-15***	***-21***	***-27***	***-17***	***-17***	***-23***
2	84	***-23***	***-33***	***-38***	***-26***	***-27***	***-34***
3	120	***-15***	***-25***	***-39***	***-16***	***-19***	***-27***
4	137	***-12***	***-24***	***-40***	***-15***	***-19***	***-29***

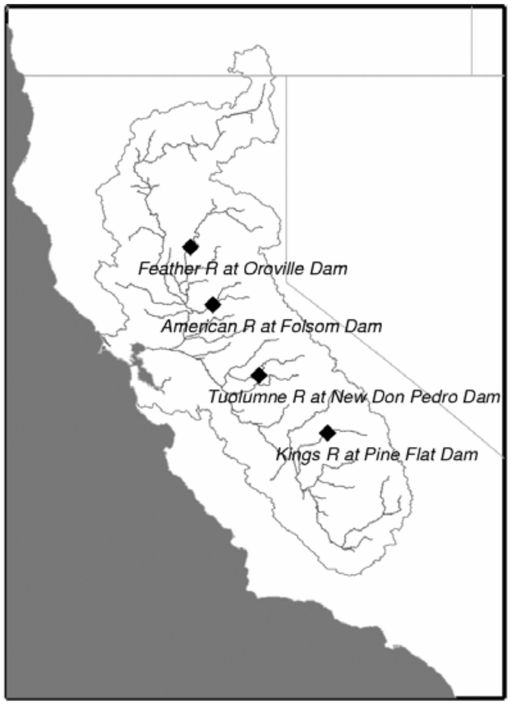

Figure 1 - Location of the outlets to the four basins included in this study. Names indicate the River and the reservoir/dam into which the river discharges

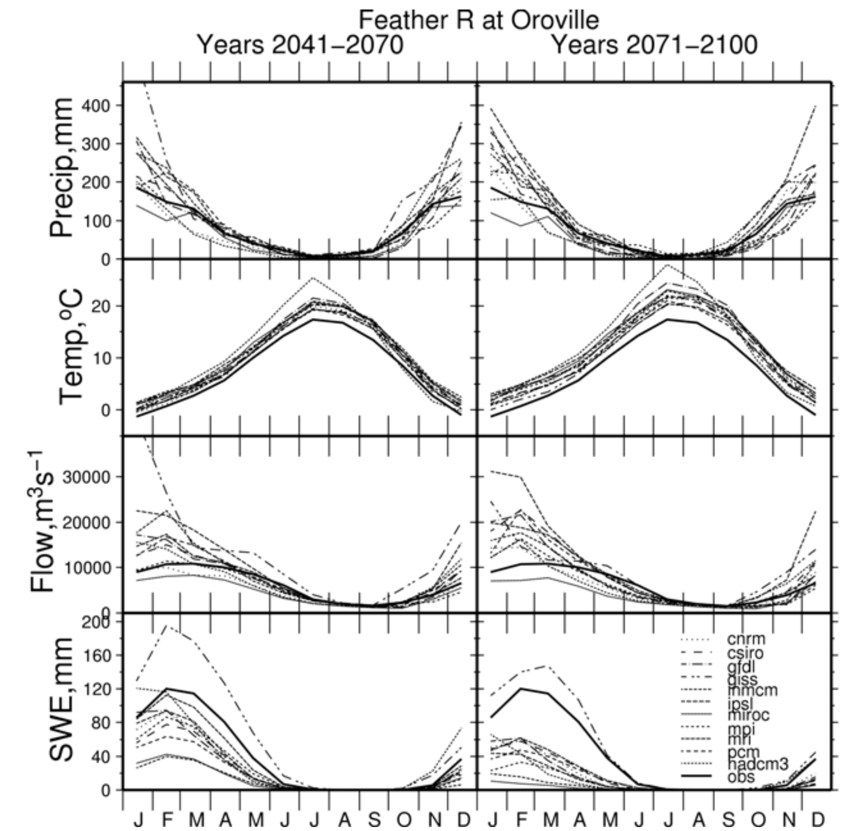

Figure 2 - For one basin, for the SRESA2 scenario, the average precipitation and temperature, streamflow at the outlet point , and basin average snow water equivalent averaged over two 30-year periods. The thicker line labeled "obs" represents the baseline average for 1961-1990.