

Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary

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[1] California's primary hydrologic system, the San Francisco estuary and its upstream watershed, is vulnerable to the regional hydrologic consequences of projected global climate change. Projected temperature anomalies from a global climate model are used to drive a combined model of watershed hydrology and estuarine dynamics. By 2090, a projected temperature increase of 2.1°C results in a loss of about half of the average April snowpack storage, with greatest losses in the northern headwaters. Consequently, spring runoff is reduced by 5.6 km³ (~20% of historical annual runoff), with associated increases in winter flood peaks. The smaller spring flows yield spring/summer salinity increases of up to 9 psu, with larger increases in wet years. **INDEX TERMS:** 3210 Mathematical Geophysics: Modeling; 1833 Hydrology: Hydroclimatology; 1655 Global Change: Water Cycles (1836); 1860 Hydrology: Runoff and Streamflow; 4235 Oceanography General: Estuarine Processes. **Citation:** Knowles, N., and D. R. Cayan, Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary, *Geophys. Res. Lett.*, 29(18), 1891, doi:10.1029/2001GL014339, 2002.

1. Introduction

[2] In light of mounting evidence of anthropogenic warming of the Earth's oceans and atmosphere [e.g., Levitus et al., 2001; National Research Council, 2001], the consequences of projected future global and regional warming for the San Francisco estuary and its watershed (Figure 1) need to be carefully evaluated. The San Francisco estuary is the third largest estuary in the United States, supporting a wide variety of flora and fauna, including many endangered species. The Delta of the Sacramento and San Joaquin Rivers, which provide nearly all the estuary's freshwater, is also the hub of California's freshwater management infrastructure. This freshwater storage and transport system is vital to the State's economy, providing water to meet agricultural, municipal, industrial, and environmental demands.

[3] California's heavy dependence on reservoirs and snowpack for flood prevention and freshwater storage makes it especially vulnerable to projected hydrologic changes. Water quality in the San Francisco estuary is strongly driven by the volume and timing of freshwater

inflows, so upstream hydrologic changes would impact the not only the watershed, but also the estuarine ecosystems.

[4] From December through March, the Sacramento-San Joaquin watershed receives an average 30–40 km³ of freshwater as rain and snow. The Sacramento River is sourced in the moderate altitude Cascades and northern Sierra, while San Joaquin flows are generated in the high southern Sierra. California depends on artificial storage (reservoirs) and natural storage (snowpack) to make this supply last the rest of the year. Snowpack alone delays an average of 40% of the annual supply until after April 1st [Roos, 1989]. Total storage in the watershed's major reservoirs is about 35 km³, roughly the size of the average annual freshwater endowment. Highly variable winter and spring runoff is managed as a flood hazard, meaning it is released from reservoirs as quickly as necessary to maintain sufficient flood control storage space. After April, the management goal is reservoir recharge, accumulating the steady stream of snowmelt runoff for distribution later in the year.

[5] Warmer conditions would reduce the volume of the snowpack, contributing to higher flood peaks during the rainy season and reduced warm-season flows after April. Possible precursory signs of a warming trend include a long-term decrease in the fraction of freshwater inflows arriving in the spring [Aguado et al., 1992; Dettinger and Cayan, 1995; Roos, 1991; Wahl, 1992], earlier onset of spring plant blooms and of the initial spring snowmelt runoff pulse [Cayan et al., 2001; Peterson et al., 2000], and increased spring salinity in the estuary [Knowles, 2000; Peterson et al., 1995].

[6] A sustained warming trend would alter hydrologic conditions throughout the watershed and change the annual salinity cycle of the San Francisco estuary. The present study uses a relatively well-resolved, watershed-wide hydrologic model, combined with a model of estuarine dynamics, to assess these impacts. This article presents new estimates of warming-induced changes in snowpack and streamflow throughout the watershed, and of changes in estuarine salinity, for the remainder of this century.

2. Methods

[7] The Parallel Climate Model (PCM) is a numerical model of the global climate system that couples atmospheric, land surface, oceanic and sea-ice components [Washington et al., 2000]. It has recently been shown to accurately



Figure 1. The San Francisco estuary and its watershed, with major geographic features indicated. The inset shows the watershed's location within California.

reproduce an observed long-term rise in the temperature of the world's oceans [Barnett *et al.*, 2001] and otherwise produces climate simulations that compare favorably to observations. In California, this model projects a near-surface air temperature increase of just over 2°C during the course of the 21st century, in response to a hypothesized "business-as-usual" buildup of greenhouse gases in the atmosphere. This is a relatively small warming in comparison to most other climate models [see Gleick, 2000].

[8] While there is a consensus among global models on the occurrence and approximate magnitude of temperature increase, precipitation is a much more variable process. In response to the projected 21st century greenhouse-gas buildup, the PCM projects relatively little overall change in the amount of precipitation California receives. During the recent National Climate Change Impacts Assessment [Felzer, 1999], however, other models have forecast increases. Thus, the magnitude and even the direction of possible precipitation changes in California remains an area of considerable uncertainty. Because of the great uncertainty shrouding precipitation projection at present, we focus here solely on the effect of temperature change on the San Francisco estuary and watershed, with the implicit assumption that the PCM forecast of (essentially) no precipitation trend is accurate.

[9] To isolate the effects of temperature increase, simulated mean monthly temperatures from a 1995–2099 PCM run were averaged over the watershed to generate 12 mean monthly temperature anomalies for each of the periods 2020–2039, 2050–2069 and 2080–2099, relative to 1995–2005 mean monthly values. The resulting anomalies represent estimates of mean monthly temperature changes averaged over the Sacramento–San Joaquin watershed for the years 2030, 2060 and 2090, relative to present conditions.

[10] These 3 sets of 12 monthly mean anomalies were added separately to historical daily temperature time series distributed over the watershed from water years (WY) 1965–1987. This 23-year period was chosen for its

complete coverage of required model input data. Along with the adjusted temperature time series, daily historical (unchanged) precipitation data from the same period were used as inputs to a hydrologic model of the watershed, resulting in three simulations of watershed snowpack and streamflow representing the watershed's hydrologic behavior under projected 2030, 2060 and 2090 temperature regimes. A fourth control simulation was performed using unchanged WY 1965–1987 precipitation and temperature to represent the watershed's present hydrologic regime.

[11] The Bay-Delta watershed model (BDWM) used for these simulations is a physically based, soil moisture accounting model with a daily time step and a horizontal resolution of 4 km [Knowles, 2000]. The snow component of this model is an adaptation of the Utah Energy Balance (UEB) snow model [Tarboton and Luce, 1996], which has been shown to accurately reproduce Sierran snowpack variability. An important feature of the model is that it is not calibrated to any particular historical hydrologic regime, making it particularly well suited for studies of climate change.

[12] The final step in these simulations was to use output from the four 23-year BDWM runs to estimate changes in total watershed outflow ("Delta outflow") in 2030, 2060 and 2090, relative to present conditions. These simulated changes in Delta outflow were added to historical (1965–1987), observation-based estimates of outflow [CDWR, 1999] to generate estimates of freshwater inflows to the estuary that would occur under the projected increases in temperature. The implicit assumption that management effects on Delta outflow would be the same under the projected warmed conditions as they have been under recent historical conditions is of course an oversimplification; this assumption is discussed further below. Adjusted Delta outflow time series were used to drive four 23-year simulations of estuarine salinity. These four simulations represent the range of hydrologic variability occurring or projected to occur under 2000, 2030, 2060, and 2090 conditions.

[13] The Uncles-Peterson (U-P) estuarine model, an advective-diffusive intertidal box model of the San Francisco estuary with a daily time step, was used to perform the estuary simulations. This model has been applied in several previous studies of the estuary and has been shown to accurately reproduce salinities at weekly to interannual time

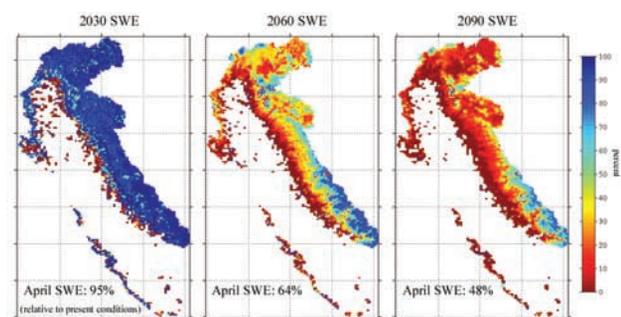


Figure 2. Simulated snow water equivalent (SWE) under a projected temperature increase for the periods 2020–2039 (0.6°C warming), 2050–2069 (1.6°C) and 2080–2099 (2.1°C), expressed as a percentage of average present conditions.

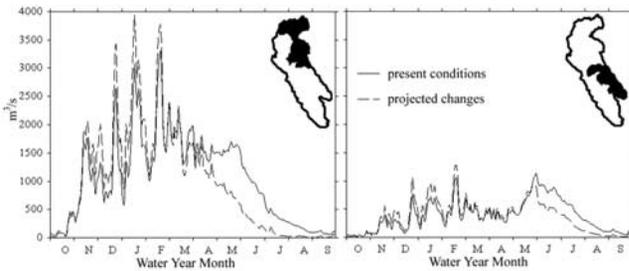


Figure 3. Projected mean annual hydrographs of northern and southern headwater regions for 2090, compared to present conditions.

scales over a wide range of flow regimes [e.g., Knowles et al., 1997; Knowles et al., 1998; Peterson et al., 1995].

3. Results

3.1. Snowpack Changes

[14] Simulated snowpack under warmed conditions (Figure 2) depicts a severe loss of snow as indicated by changes in the snow water equivalent (SWE) by 2090. By 2030, the watershed-averaged temperature is projected, under the “business-as-usual” scenario, to rise by about 0.6°C, resulting in a minor reduction in snowpack at lower elevations. April SWE, typically the snowpack’s annual apex, is reduced by only 5% compared to present conditions. However, an increase of 1.6°C by 2060 causes the loss of over 1/3rd of the total April snowpack. This loss is focused in mid to lower elevations, since snowpack there is more sensitive to temperature changes than at higher, colder elevations. Regionally, this means that the northern Sierra and Cascades experience the greatest loss. Note that since overall precipitation is conserved in this projection, the lost snowpack appears instead as early runoff.

[15] By 2090, average temperatures are projected to have increased 2.1°C, resulting in a loss of about 1/2 of the watershed’s total April snowpack. Again, the loss is most severe in the northern Sierra and Cascades, which would lose 66% of their April snowpack, but the southern Sierra would also be strongly impacted, losing 43% of their April snowpack.

3.2. Outflow Changes

[16] The loss of snowpack indicated above would have large effects on streamflows throughout the watershed. The mean annual (water year) hydrographs of the total outflow from the northern and southern headwaters (projections for 2090 are shown in Figure 3) reflect the changing flow patterns in these two regions. In general, the loss of snowpack results in higher runoff peaks prior to April and reduced snowmelt-driven flows in subsequent months.

[17] As with the relatively unchanged 2030 snowpack, projected 2030 outflows (not shown) are very similar to present conditions. By 2060 (not shown), both the northern (Sacramento) and the southern (San Joaquin) headwaters show the effect of reduced snowpack, with the largest effect in the north. The April–July fraction of total annual flow in the northern headwaters is reduced from 0.36 in 2030 to 0.26 in 2060. Combined with the smaller reduction in the

south, this represents over 3 km³ (~2.5 maf) of runoff shifting from post-April 1 to pre-April 1 flows.

[18] By 2090, both regions show significantly impacted hydrographs, with a loss of 1.2 km³ April–July runoff in the south and 4.4 km³ in the north, for a total loss of 5.6 km³ (~4.5 maf), about 20% of historical annual flow volume.

3.3. Salinity Changes

[19] As described earlier, the approach used to project salinity changes ignores the likelihood that reservoir operations would attempt to mitigate the effects of warming. However, considering how the salinity projections differ in wet versus dry years provides additional insight.

[20] Figure 4 shows the present and projected mean annual cycles of simulated San Pablo Bay salinity for wet and dry conditions. San Pablo Bay is the northwestern-most subembayment of the San Francisco estuary. These composites were produced with the 5 wettest and 5 driest years of the simulations used to generate the salinity change estimates. In dry years, estimates of salinity change between present and 2090 conditions are on the order of 1–3 psu. However, dry-year conditions would leave reservoirs with more space to mitigate the hydrologic effects of temperature change. As a result, it may be likely that during dry years, salinity impacts could be even less than shown by these simulations.

[21] Conversely, wet years bring precisely the type of conditions that would handicap the reservoirs’ ability to mitigate change. The need for increased flood control capacity, combined with severely reduced snowmelt runoff, could limit the options of water managers. The resulting lower-than-historical dry season freshwater reserves could result in salinity increases greater than the 5–9 psu shown here.

4. Discussion

[22] Under the “business-as-usual” temperature increase scenario examined here, the diminished snowpack and earlier runoff of water that is currently used to recharge California reservoirs would bring adverse impacts to estuarine and watershed ecosystems and all who depend on the freshwater supply infrastructure. Increased winter flooding and summer saline intrusion contaminating freshwater supplies are among the potential hazards. Recent works by Snyder et al. [2002] using a regional climate model suggests that warming may increase with elevation, meaning snowpack losses could be larger than those presented here. High

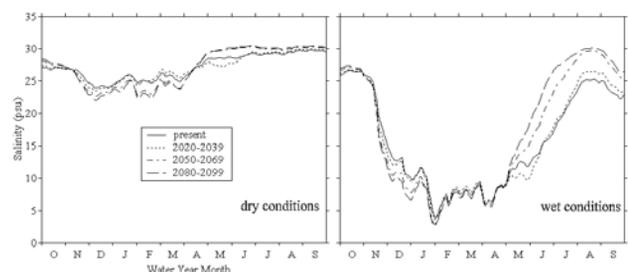


Figure 4. Wet- and dry-year composite mean annual cycles of simulated San Pablo Bay salinity for periods 1995–2005, 2020–2039, 2050–2069 and 2080–2099. Differences result from changes in total watershed outflow as simulated by the watershed model.

salinities would likely be exacerbated by sea level rise, which is projected to proceed at a rate of 50 cm over the next 100 years [IPCC, 2001]. The increased possibility of levee failure that would result from higher wet-season flows and increased sea level could have additional impacts.

[23] Superimposing projected temperature anomalies on modern climate seems to provide a reasonable methodology for evaluating potential climate change impacts in California. The estimates of hydrologic change presented here agree well with the results of other studies of the potential effects of climate change in this watershed [Dettinger, personal communication; Gleick, 1987; Gleick and Chalecki, 1999; Jeton et al., 1996; Lettenmaier and Gan, 1990; Roos, 1989] but is important to recognize that this study represents one possible climate change scenario. The range of warming estimates from the various climate models is large—from 1–6°C over the next 100 years [IPCC, 2001]. Clearly, a smaller increase than the ~2°C used in the present study would lessen the impacts on snow, streamflow and salinity discussed above, while the higher increases projected by some climate models would magnify these impacts. Changes in precipitation as a result of global climate change are even more ambiguous than temperature change. Considerable uncertainty therefore exists in the hydrologic consequences of climate change. However, some consequences, such as increased flooding potential, are quite likely under most scenarios.

[24] This study illustrates the distribution of the very sensitive response of snowpack and streamflow throughout the watershed. The hydrologic and water quality changes exhibited are substantial, even though the PCM's projected temperature change of about 2°C per century is relatively conservative. These results emphasize that California's strong reliance on natural and artificial storage of freshwater will make adjusting to the hydrologic changes that seem likely to occur in the coming century a difficult challenge.

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