Recent Projections of 21st-Century Climate Change and Watershed Responses in the Sierra Nevada[1]

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In the near future, the Sierra Nevada's climate is projected to experience a new form of climate change due to increasing concentrations of greenhouse gases in the global atmosphere from the burning of fossil fuels and other human activities. If the changes occur, they presumably will be added to the large interannual and longer-term climate variations in the recent and distant past that have been described in this chapter. The projected changes include much-discussed warming trends as well as important changes in precipitation, extreme weather, and other climatic conditions, all of which may be expected to affect Sierra Nevada rivers, watersheds, landscapes, and ecosystems.

Simulated temperatures in climate-model grid cells over Northern California began to warm notably by about the 1970s in response to acceleration in the rate of greenhouse-gas buildup in the atmosphere then and are projected to warm by about +3 °C during the 21st century *(fig. 1a)*. The temperatures shown were simulated by the coupled global atmosphere-ocean-ice-land Parallel Climate Model (PCM) in response to historical and projected "business-as-usual" (BAU) future concentrations of greenhouse gases and sulfate aerosols in the atmosphere. The model, part of the Department of Energy-funded Accelerated Climate Prediction Initiative Pilot Study, yields global-warming projections that are near the cooler end of the spectrum of projections made by modern climate models and thus represent changes that are relatively minor. Projections of precipitation change over Northern California are small in this model, amounting in the simulation shown *(fig. 1b)* to no more than about a 10 percent increase. Notably, though, other projections by the same model with only slightly different initial conditions yield small decreases rather than increases. Thus we interpret the precipitation change in the projection examined here as "small," without placing much confidence in the direction of the change. Even more generally, there is essentially no consensus among current climate models as to how precipitation might change over California in response to global warming. In light of these precipitation-change uncertainties, we focus below on the watershed responses that depend least upon the eventual precipitation changes.

River-basin responses to climate variations and trends in the Sierra Nevada have been analyzed by simulating streamflow, snowpack, soil moisture, and water-balance responses to the daily climate variations spanning a 200-year period from the PCM's historical and 21st century BAU simulations. Watershed responses were simulated with spatially detailed,

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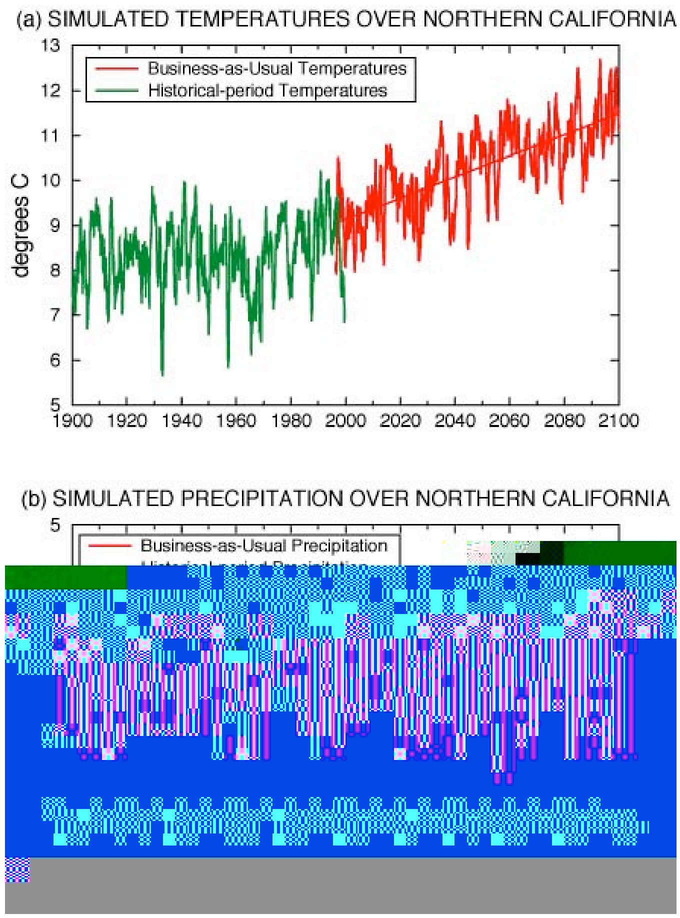

Figure 1— Simulated annual mean temperatures (a) and precipitation (b) in Parallel-Climate Model grid cells over Northern California, from 1900 to 2100, where the historical simulation is forced with observed historical radiative forcings and the business-as-usual future simulation is forced with greenhouse-gas increases that are extensions of historical growth rates. Straight lines are linear-regression fits.

physically based watershed models of several Sierra Nevada river basins but are discussed here in terms of results from a model of the Merced River above Happy Isles Bridge at the head of Yosemite Valley. The historical simulations yielded stationary climate and hydrologic variations until the 1970s when temperatures begin to warm noticeably. This warming resulted in a greater fraction of Sierra Nevada precipitation falling as rain rather than snow *(fig. 2),* earlier snowmelt *(fig. 3),* and earlier streamflow peaks. The projected future climate variations continue those trends through the 21st century with a hastening of snowmelt and streamflow within the seasonal cycle by almost a month. By the end of the century, 30 percent less water arrives in important reservoirs during the critical April–July snowmelt-runoff season *(fig. 4)*. These reductions in snowpack are projected to occur in response to the warming climate under most climate scenarios unless substantially more (order of two times or more) winter precipitation falls; even in that case, although enough additional snowpack could form to yield a healthy spring snowmelt, the snow-covered areas still would be substantially reduced. In any event, the earlier runoff comes partly in the form of increased winter floods so that the changes would pose challenges to reservoir managers and could result in significant geomorphic and ecologic responses along Sierra Nevada rivers. With snowmelt and runoff occurring earlier in the year, soil moisture reservoirs dry

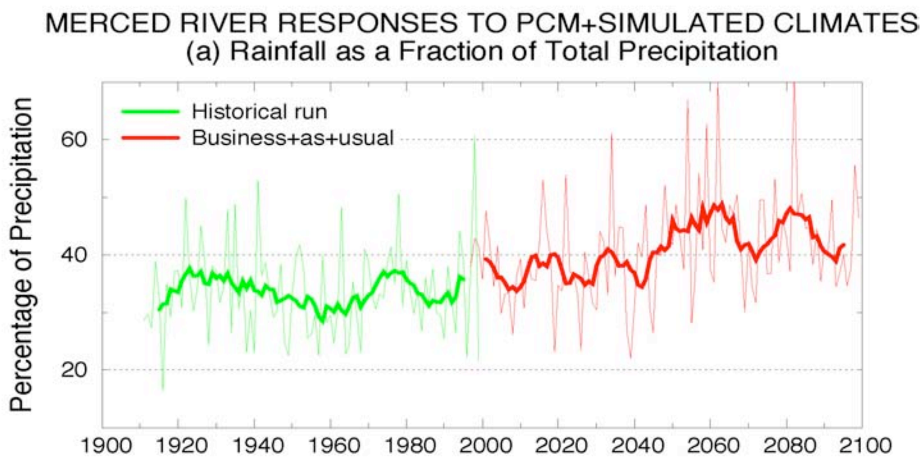

Figure 2— Water-year fractions of total precipitation as rainfall in the Merced River basin in response to PCM-simulated climates. Heavy curves are 9-year moving averages.

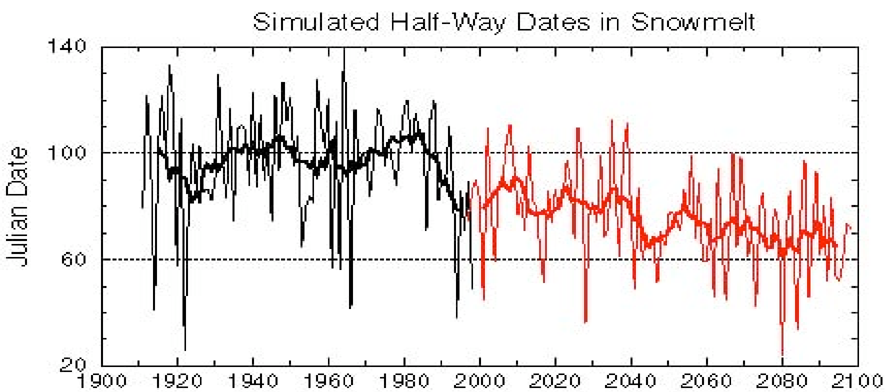

Figure 3— Water-year fractions of total precipitation as water-year centroids of daily snowmelt rates in the Merced River basin in response to PCM-simulated climates. Heavy curves are 9-year moving averages.

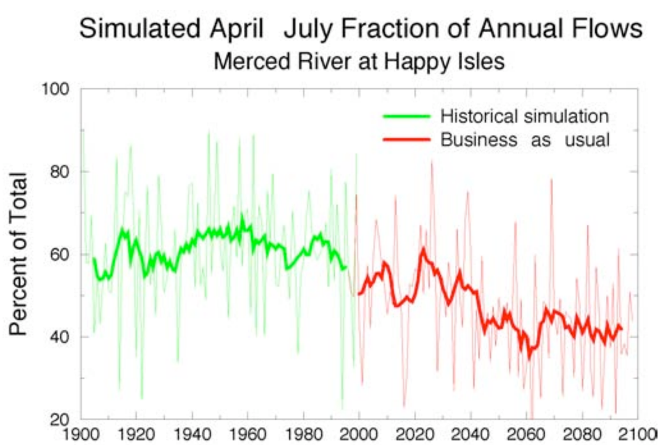

Figure 4— Fractions of each water year's simulated total streamflow that occur during April–July in the Merced River at Happy Isles in response to PCM-simulated climates. Heavy curves are 9-yr moving averages.

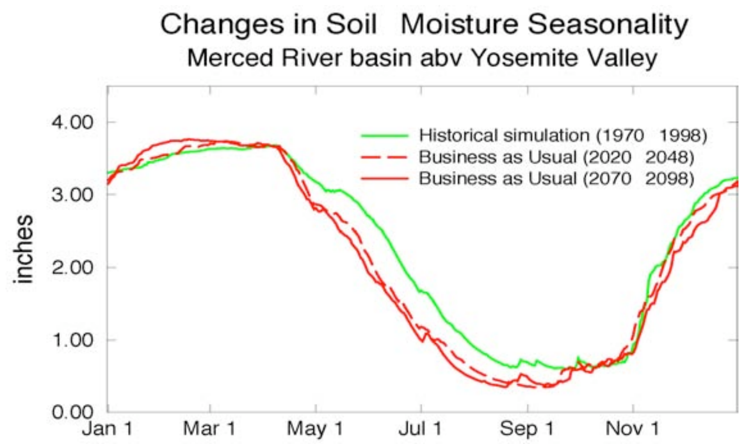

Figure 5— Simulated seasonal cycles of basin-average soil-moisture contents in Merced River above Happy Isles in response to PCM-simulated climates during selected interdecadal intervals.

out earlier and by summer are more severely depleted *(fig. 5)*. By about 2030, the projected hydrologic simulations of other river basins, hydrologic simulations at the scale of the entire Sierra Nevada, and projections of wildfire-start statistics under the resulting hydroclimatic conditions indicate that the results from the simulations of the Merced River basin considered here are representative of the kinds of hydrologic changes that will be widespread in the range. Thus, it appears likely that climate change would affect hazards and ecosystems significantly and throughout the range. The riverine, ecological, fire, and geomorphic consequences are far from understood but are likely to be of considerable management concern. Considerations for resource managers confronting 21st-century landscape issues in the Sierra Nevada include:

Climate projections by current climate models are fairly unanimous in calling for warming of at least a few degrees over the Sierra Nevada, and this warming may be increased over the range by orographic effects (that is, effects resulting from the presence of mountains).

Projections of future precipitation are much less consistent so that we do not yet know if the Sierra Nevada will be wetter or drier.

Even the modest climate changes projected by the PCM (with a conservative value for warming and small precipitation changes) would probably be enough to change the rivers, landscape, and ecology of the Sierra Nevada, yielding: (1) substantial changes in extreme temperature episodes, for example, fewer frosts and more heat waves; (2) substantial reductions in spring snowpack (unless large increases in precipitation are experienced), earlier snowmelt, and more runoff in winter with less in spring and summer; (3) more winter flooding; and (4) drier summer soils (and vegetation) with more opportunities for wildfire.

The projections used here suggest that global warming at the accelerated pace that will characterize the 21st century is already about 30 years old; thus, changes in the recent past must also be considered in light of global change. For example, changes in streamflow timing are already known to be widespread across most of the Western states.

The consequences of climate change are likely to be significant, but in light of current uncertainties about their nature, policies that promote flexibility and resilience seem most prudent.