The State of Climate Change Science for Water Resources Operations, Planning, and Management

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Executive Summary and Recommendations

Our understanding of climate processes today includes the expectation that climate will be changing over the course of the next century to an extent that these changes must be accounted for in the water resources planning process. Much of our expectations arise from research sponsored by the California Energy Commission through their Public Interest in Energy Research (PIER) program. An update summary of their efforts is provided in a report by Moser and Franco (2008).

The current expectations for future changes in California's climate include:

- Mean temperature increases from 2 to 6 degree C. California's complex terrain will modulate the value locally.
- Unknown change to precipitation total but an increase in extreme wet and dry conditions. More precipitation will fall as rain than snow in higher elevations.
- Decreased snowpack particularly in the northern Sierra (up to 90% by 2100) and earlier melt time. Less mountain block recharge from snowpack expected with implications for long-term support of regional aquifers.
- Annual runoff concentrated more in winter months with more variability and greater extremes.
- Sea level rise up to 55 inches with the potential for higher rises
- Ecosystem challenges increased due to exacerbation of existing threats from above changes

These changes will increase the vulnerability of water resources infrastructure including flood control, water supply and wastewater treatment and disposal. The changes will challenge the current operations procedures for our water resources infrastructure and impact the planning for new projects. While many mitigation efforts are underway as part of Assembly Bill 32's implementation, adaptation strategies such as those put forward in the DWR's adaptation white paper (DWR, 2008a) will be needed to accommodate the changes that will occur due to climate change.

Climate change science provides the basis for both mitigation and adaptation strategies for water resources planning and management. The state of the science at the time of the second California Climate Action Team (CAT) assessment is reviewed in this report. Water resources planning and management efforts related to climate change can be based on information contained in the observed record, make use of paleoclimate reconstructions to expand the magnitude of extremes and variability of climate, and use information from future projections of climate over the next century. The use of climate change information in water resources planning and management tools is reviewed followed by an assessment of the state of the science in observations, paleoclimate, and future projections.

Based on this review, the following recommendations are made to advance the science further. These recommendations are consistent with the outcomes of the Western Governor's Association Western States Water Council California Department of Water Resources Climate Change Research Needs Workshop held in May 2007 (Jones et al, 2007).

Climate change information can be used as inputs to watershed hydrology, water allocation, and water quality models for water resources analyses. Current frameworks for water resources simulation rely on manipulating the climate change simulation results to fit the existing input structure of the models. In some cases this means scaling a historical hydrological pattern to reflect timing or magnitude shifts in precipitation or runoff. In other cases the information from the climate change simulations must be aggregated or disaggregated to fit the input structure of the model. This effort of bringing climate change science into the planning arena is an area of ongoing development. Recommendations for future efforts include:

- Refine the planning models' ability to incorporate climate change information from observations, paleoclimate, and future projections as input
- Move climate change studies towards the development of adaptation strategies that incorporate risk assessments of the potential impacts that have been identified
- Provide feedback to science on data needs and the scale and format in which it is needed

There are a multitude of observation networks to monitor different climate variables in California. Not all of the networks were set up for climate monitoring and care should be taken to evaluate the metadata when using the data for climate analyses. Recommendations for future efforts in observation networks include:

- Compile a review of data sources for California including parameters measured, length of record and associated metadata.
- Create a climate data portal to centralize access to the diverse array of networks in the state
- Determine additional monitoring needs to track climate change such as monitoring for tracking the migration of the rain/snow transition zone as well as monitoring high elevation processes.

- Investigate relations of inter-annual and multi-decadal variability within observed data and its potential change and interaction with global warming.

Paleoclimate studies offer an extension of the observed record documenting periods of greater variability and more extreme climate conditions. Data for water resources applications can come from proxies like tree rings, lake sediments, and pollen. These reconstructed hydrologic time series can be used in planning studies to examine system performance and response under a wider range of values with a physical basis. Recommendations for future efforts in paleoclimate studies include:

- Build a library of paleoclimate applications for water resources studies to serve as examples for interested water agencies
- Incorporate paleoclimate data sets into climate data archive accessible through data portal recommended above
- Extend paleoclimate studies to more regions in California

Future projections of climate rely on simulations produced by Global Circulation Models (GCMs). GCM simulations run for different scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) produce data stored in the Lawrence Livermore National Lab World Climate Research Program Coupled Model Intercomparison Project 3 (WCRP CMIP 3) archive (Meehl et al., 2007). Bader et al. (2007) show that using an ensemble of future projections is better than using a single model based on analyses of historical period simulations. However, the spatial scale needed for water resources studies is much smaller than the spatial scales of the GCM simulations. Because of this, downscaling efforts are needed. Downscaling can be accomplished using a statistical basis, a dynamical basis, or a combination of the two. A database of statistically downscaled data developed by researchers from Santa Clara University, Lawrence Livermore National Laboratory and the Bureau of Reclamation (Maurer et al., 2007) is available at a website hosted by Lawrence Livermore National Laboratory at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.htmln. Dynamic downscaling and combined methods are much less common and data is not readily available like the statistical downscaling data. Recommendations for future efforts in the future climate projections include:

- Pursue further development of parameterized processes in GCMs to better reproduce atmospheric circulation processes critical to California's water resources including the southwest summer monsoon.
- Develop regional coupled models to illuminate details of land-atmosphere-ocean interactions at the local scale for California
- Explore further downscaling approaches and determine advantages and disadvantages of each method or combinations of methods.

- Expand the variables that are downscaled beyond just temperature and precipitation to include parameters such as wind speed, relative humidity, etc.

Details of the state of the science review and additional references are provided in the following sections.

Background

Climate plays a central role in the operation planning and management of water resources systems for water supply, flood management, and environmental stewardship. Our expectations of the timing and form of precipitation, the timing, magnitude and distribution of runoff, and the availability of water for beneficial use are based on our understanding of the climate system and our experience with meteorological and hydrological events.

We have arrived at a point in history where our future expectations of climate differ significantly from our past experience because of climate change. This mismatch between past and future raises significant issues related to water resources operations, planning and management. Questions arise related to the function and utility of current infrastructure operation and maintenance as well as to the information used for project planning. In seeking answers to these questions we need to assess what is available from the scientific community regarding the projection of future climate.

This document assesses the state of climate change science available for California water resources operations, planning, and management at the time of the second Climate Action Team (CAT) assessment and Water Plan Update 2009. The document examines observations, paleoclimate, future projections, and planning and assessment tools that are used to inform climate change mitigation and adaptation efforts.

Climate change is a dynamic and popular field for both research and management. Water resources managers looking for information and resources to guide their adaptation and mitigation efforts can easily become overwhelmed at the breadth and depth of information available. In addition to reviewing the state of climate change science, this document provides a pertinent reference list to serve as a starting point for managers seeking to gain information on the topic.

Climate change science comes from many sources as do recommendations for its use in adaptation and mitigation strategies. International, national, regional, statewide, and local groups and agencies provide information that has applicability in California. These groups and some of their recent documentation are described below.

At the international level the Intergovernmental Panel on Climate Change (IPCC) is providing information on global level changes and expectations of large scale impacts on society and resources. Every five years the IPCC releases assessment reports updating consensus climate change projections and their perceived impacts. The latest effort is the fourth assessment (AR4) that was released in 2007 (IPCC, 2007).

At the national level, the United States Climate Change Science Program coordinates climate change research activities of US government agencies. Their latest assessment (CCSP, 2007) includes an overview of climate change impacts on agriculture, land and water resources, and biodiversity from an ecosystem perspective.

The Western Governors' Association and Western States Water Council have provided guidance and recommendations for federal agencies on many topics including climate change. In November of 2007, the WGA/WSWC held a workshop on climate change to develop a list of climate change research needs (Jones et al., 2007). These recommendations include a centralized access point for climate change data, and improved interaction between agencies and the university research community.

Climate change efforts at the state level have been in progress since the late 1980s. These efforts expanded and became more organized as a result of Governor Arnold Schwarzenegger's 2005 Executive Order S-03. This executive order not only set goals for greenhouse gas reductions, but set up a Climate Action Team (CAT) headed by the California Environmental Protection Agency. One of the charges of the CAT is to produce biennial reports on the incorporation of climate change into state agency programs and processes. The second report is in progress with a target release date in early 2009. Information on the CAT and publications generated from the effort can be found at http://climatechange.ca.gov.

In addition to the CAT, several state agencies have their own climate change programs. The California Energy Commission (CEC) has a Public Interest in Energy Research (PIER) program that includes significant funding for climate change research. Each year in September, the CEC holds a climate change conference in Sacramento that showcases research results from the PIER program. An overview of the state of the program can be found in Moser and Cayan (2008).

The California Department of Water Resources (DWR) also has a climate change program. This program works in partnership with the CEC to provide guidance on water resources related efforts. The program also produces technical reports on efforts to incorporate climate change into its water resources planning and management (DWR, 2006, 2008b). Climate change is also incorporated into DWR's Water Plan Updates (DWR, 2005a). A literature review of peer-reviewed research on California's climate and climate change was provided by Kiparsky and Gleick (2005). An article by Roos (2005) reviewed potential impacts of climate change on California's water resources system along with some possible responses by water managers and planners.

Recently, DWR has released special reports on climate change in association with select conferences. In 2005, a report on the Colorado River Climate (DWR, 2005b) was released in association with the Association of California Water Agencies and Colorado River Water Users Association Conferences. In 2008, a report on climate change and border water issues (DWR, 2008b) was released in association with the 26th Border Governor's Conference.

Climate change information is also being incorporated into the CALFED Science Program (Dettinger and Culberson, 2008), and can be found in organizational publications like the Watershed Management Council's (WMC) 2005 report Changing Climate Changing Watersheds (WMC, 2005). This broad array of agency effort has produced a wealth of climate change information from the research community. An overview of the latest expectations of climate change impacts on California's water resources is presented in the next section.

Expected California Climate Change Impacts in Water Resources Area

The impacts of climate change on water resources will be felt through changes in temperature, precipitation and runoff, and sea level rise. The current expectations for changes in California's climate are illustrated in Figure 1.

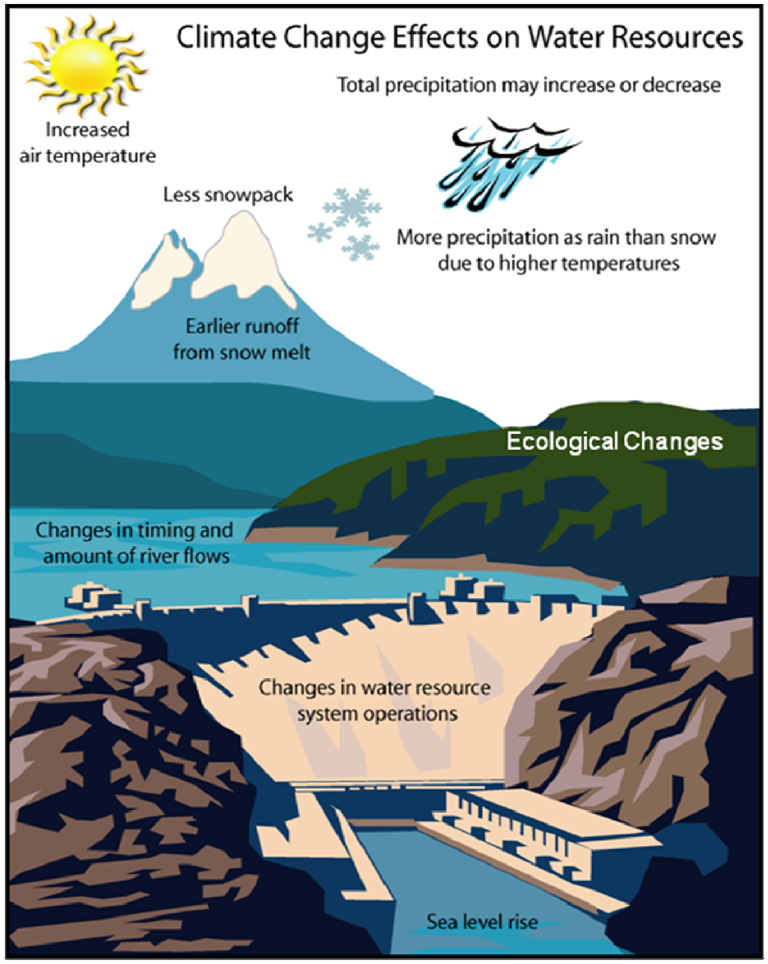


Figure 1. Depiction of potential climate change impacts on California water resources

Details of these changes include:

- Mean annual temperature increases from 2 to 6 degree C. California's complex terrain will modulate the value locally.
- Unknown change to annual precipitation total but an increase in extreme wet and dry conditions is expected. More precipitation will fall as rain than snow in the middle elevations of the mountains.
- Decreased seasonal snowpack accumulation particularly in the northern Sierra (up to 90% by 2100) and earlier melt time.
- Less mountain block recharge from snowpack expected with possible implications for long-term support of regional aquifers.
- Annual runoff concentrated more in winter months with more variability and greater extremes.
- Sea level rise up to 55 inches with the potential for higher rises if ice sheets collapse.
- Ecosystem challenges increased due to exacerbation of existing threats from above changes.

Detailed descriptions of the expected changes can be found in the CAT Assessment Reports (California Climate Change Center, 2006) as well as in reports to the CEC's PIER program related to climate change. A listing of select references on climate change impacts to California's water resources is provided in Table 1.

As improvements are made to the science of future projections and their incorporation into resource management applications, refined expectations can be made. These expectations can then be incorporated into water resources planning and management studies that can help inform the development of adaptation strategies. In the following sections of this document, the state of the science of using climate change information in water resources planning and management tools is covered first. Then the state of the science in observations, paleoclimate, future projections of climate change is reviewed. The document concludes with a summary assessment and recommendations for future efforts.

Table 1 - Select references of climate change impact studies for California water resources

Study Type	Reference
Literature Review	Kiparsky and Gleick (2005)
Temperature and Precipitation	Cayan et al. (2008c) Dettinger et al. (2005)
Snowpack	DWR (2006) Knowles and Cayan (2004) Dettinger et al. (2004) Snyder et al. (2002) Gleick and Chalecki (1999) Jeton et al. (1996) Lettenmaier and Gan (1990) Roos (1987)

	Gleick (1987)
Runoff	Maurer and Duffy (2005) Kim (2005) Christensen et al. (2004) Van Rheenen et al (2004) Wood et al (2004) Miller (2003) Wilby and Dettinger (2000) Knowles and Cayan (2001) Miller et al. (1999) Stewart et al. (2004) Revelle and Waggoner (1983)
Sea Level Rise	DWR (2009) Cayan et al. (2008a, 2008b) CALFED ISB (2007)

Bringing Climate Change Science into Water Resources Operations, Planning and Management

In California, DWR has begun the process of incorporating climate change information into its planning processes. Additional efforts by the research community have been funded by the California Energy Commission with its PIER Program as noted in Moser and Franco (2008).

In order to bring climate change science into the planning process, some effort is required to manipulate the data produced by climate change simulations into data that can be used by planning models. In some cases it is a matter of some additional data manipulations that can be accomplished on a spreadsheet. In other cases, additional modeling steps are required to generate the appropriate planning process input.

Indeed future projections of snowpack, runoff, and sea level all require additional modeling efforts. These efforts can be correlation and regression simulations such as Rahmstorf's sea level rise model (Rahmstorf, 2007) or they can be process simulation models like the Variable Infiltration Capacity (VIC) Model (Wood et al., 2004) or the USGS watershed model PRMS (Leavesley et al., 1983). Results from these models can then be used in planning models such as DWR's CALSIM II model (Draper et al., 2004). Details of the latest efforts by the Department using these models can be found in DWR (2009).

The application of these models for water resources assessments have focused on determining impacts to current operations and management practices based on the results of a select subset of available future projections, observations, and in some cases the use of paleoclimate reconstructions. As a result, key vulnerabilities in water resources operations and management have been identified. The next step in the process is to start developing adaptation strategies that consider the impact assessments from a risk-based point of view. Because climate change will manifest itself differently in different locations of the state, it is important to begin to consider location specific risks of impacts and to begin to identify location specific mitigation and adaptation strategies that can be pursued. These strategies can adapt as improved information becomes available or as changes are realized for a given location. These efforts can help inform the scientific community as to what information is needed from observations, paleoclimate reconstructions and future projections. The current state of the science in these areas is reviewed in the following sections.

Observation Networks and Monitoring Climate Change

A multitude of observation networks exist in California that record data related to our climate. Temperature, precipitation, wind, relative humidity, snow water content, streamflow, and sea level are examples of data that is collected to address forecasting and monitoring efforts in the state. Table 2 lists some of the networks and operating agencies that collect climate related data in California. Observations may be taken by citizen volunteers, automated instruments, or satellite and the data is collected and stored by the responsible agency.

Only one of the above-mentioned networks has the mission of collecting climate data – the National Weather Service Cooperative Observer Network. The other networks were designed and constructed for other purposes. While they may have a long period of record, the data collection frequency or location may not be adequate or appropriate for climate change monitoring.

A primary example of this is snow course measurements. These measurements are taken at over 200 locations at the beginning of the month to provide data for spring runoff (April through July) forecasting purposes. Snow pillows augment this data with real-time and regular monitoring, but they are in locations that are suited to provide forecast data. Monitoring the snowpack for climate change will involve augmenting the current snowpack monitoring network with instrumentation that provides more spatial detail and instrumentation to track the rain/snow transition zone. Satellite data can play a significant role in this effort.

Observations of climate change that has already occurred can help water resources managers understand the potential vulnerabilities of their source watersheds. However, it can be challenging to gather data from the myriad of sources. It would be advantageous to have a single climate data portal that water resources managers could use to access climate data for planning and management efforts.

Observed Climate Change in the Twentieth Century

Documentation of climate change over the twentieth century in California is plentiful. Table 3 lists some of the more prominent references for observational studies in the areas of temperature, precipitation, snowpack, runoff, and sea level rise. An assessment of observed changes in the twentieth century for California was presented in the 2006 DWR report "Progress on Incorporating Climate Change into Water Resources Planning and Management". An overview of the observed changes in California is presented here for the five water resources variables mentioned above.

Table 2 – Observing Networks in California

NETWORK	Operating Agency	Data Archive Location
NWS COOP Network	NOAA	NCDC
ASOS Network	NOAA	
METAR Network	NOAA	
RAWS Network		WRCC
USDA Snowtel Network	USDA NRCS	National Water and

		Climate Center
USGS Streamgage Network	USGS	USGS
NOAA Tide Gage and Buoy Network	NOAA	
CDEC Network	DWR*	DWR
CIMIS Network	DWR	DWR

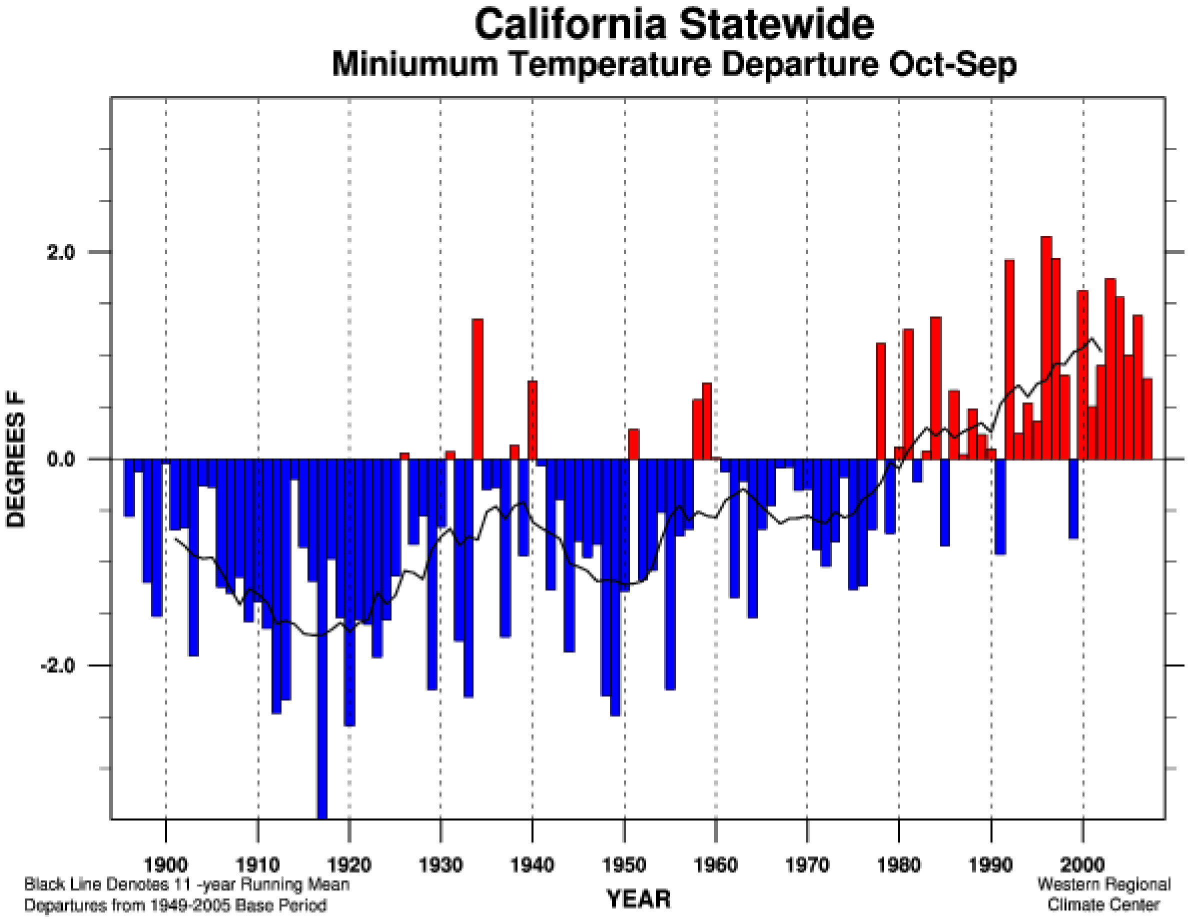
Table 3 – References for observations of 20th century climate change

Reference	Topic
Kiparsky and Gleick (2005)	Summary and literature review
Karl and Knight (1998)	Precipitation increase observations including 1-day extremes
Cayan et al. (2001)	Evaluation of spring onset in the western US
Groisman et al. (2004)	Hydrologic Cycle Change Observations
Hamlet et al. (2005)	Temperature change impacts on snowpack
Stewart et al. (2005)	Evaluation of streamflow timing in western US
Mote (2006)	Snowpack changes in western US
Knowles et al. (2007)	Rain versus snowfall trends in western US
Dettinger (2005b)	Flood generating rainfall in American River

For California, the Western Region Climate Center has developed a series of tools to view temperature and precipitation data collected by the National Weather Service's Cooperative Observer Network. These tools are housed on a web page called the California Climate Tracker (Abatzoglou et al., 2008). A sample of the plots available from the California Climate Tracker is shown in Fig. 2 and Fig. 3. Yearly values back to 1890 are plotted along with an 11-year running average. Statistics such as linear trend, extremes, mean, standard deviation and rank of the latest reading are also presented with each plot. Based on analyses using tools from the California Climate Tracker, 20th century trends have been identified in statewide and regional temperatures and precipitation and are presented in Table 4.

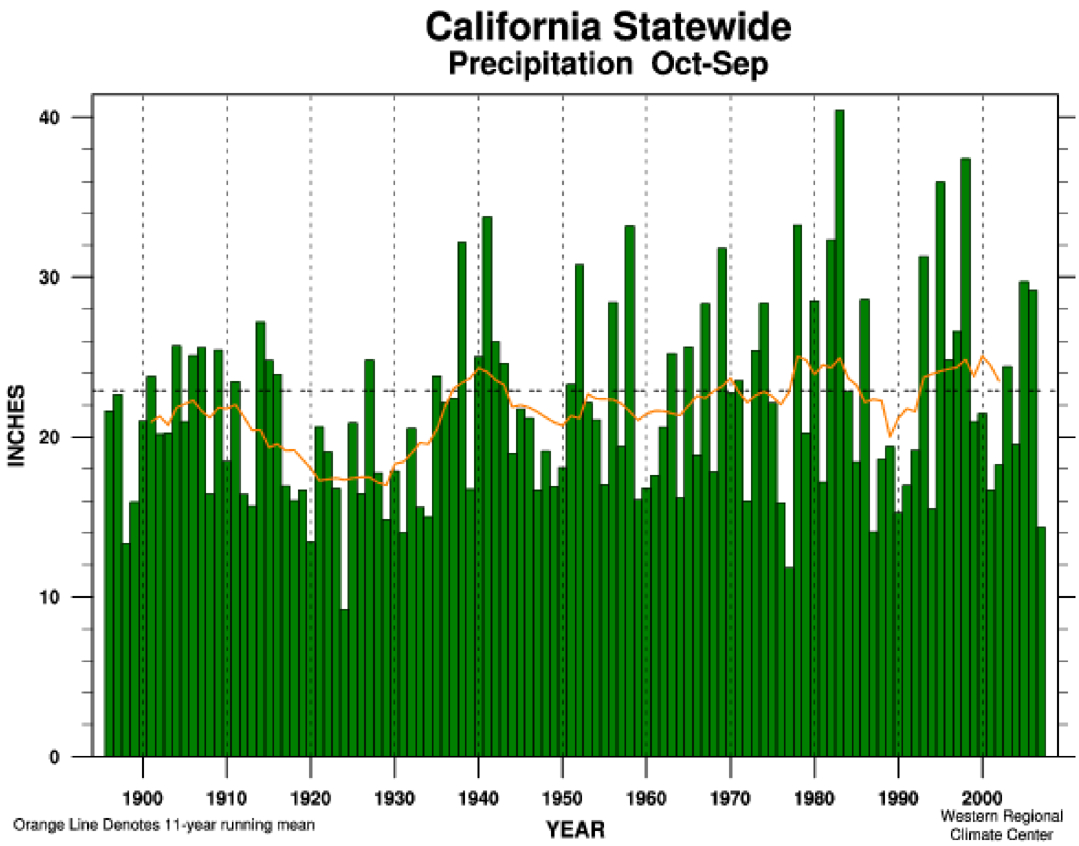
Table 4 Summary of the California Climate Tracker statewide and regional trend results.

Location	Tmax	Tavg	Tmin	Precipitation
Statewide	1.06+-0.64	1.56+-0.52	2.06+-0.51	3.87+-3.34
North Coast	1.25+-0.55	1.15+-0.48	1.05+-0.50	0.56+-8.59
Central Coast	1.09+-0.58	1.66+-0.46	2.23+-0.50	3.67+-4.63
South Coast	1.79+-0.63	2.52+-0.57	3.25+-0.59	4.04+-3.99
North Central	0.84+-0.71	1.31+-0.50	1.78+-0.52	11.28+-7.47
Sacramento Delta	1.38+-0.64	2.04+-0.48	2.71+-0.52	5.65+-3.34
Sierra Nevada	0.67+-0.84	1.44+-0.63	2.20+-0.58	5.42+-6.16
San Joaquin Valley/Tulare	0.33+-0.69	1.38+-0.53	2.44+-0.54	1.86+-2.44
Northeast	1.44+-0.90	1.54+-0.64	1.65+-0.69	2.70+-3.78
South Interior	1.60+-0.76	1.83+-0.61	2.07+-0.57	0.00+-4.15
Mohave	1.54+-0.77	1.76+-0.65	1.99+-0.61	1.75+-1.55
Sonoran	0.85+-0.72	1.48+-0.60	2.11+-0.57	1.04+-1.71



Linear Trend 1895-present		+ 2.06 ± 0.51°F/100yr		
Linear Trend 1949-present		+ 3.79 ± 1.20°F/100yr		
Linear Trend 1975-present		+ 5.00 ± 3.15°F/100yr		
Warmest Year		45.3 °F (+ 2.2 °F) in 1996	MEAN	43.1°F
Coldest Year		39.7 °F (- 3.5 °F) in 1917	STDEV	1.00 °F
Oct-Sep	2007	43.9 °F (+ 0.8 °F)	RANK	98 of 112

Figure 2. Sample temperature time series plot from the California Climate Tracker.



Linear Trend 1895-present		+ 3.87 ± 3.34 in.	(+ 16 ± 14%) per 100 yr			
Linear Trend 1949-present		+ 2.16 ± 10.39 in.	(+ 9 ± 45%) per 100 yr			
Linear Trend 1975-present		+ 1.75 ± 30.00 in.	(+ 7 ± 131%) per 100 yr			
Wettest Year		40.44 in. (176%)	in 1983		MEAN	22.90 in.
Driest Year		9.23 in. (40%)	in 1924		STDEV	6.53 in.
Oct-Sep	2007	14.36 in. (62%)			RANK	7 of 112

Figure 3. Sample precipitation time series plot from the California Climate Tracker

As was mentioned above, snowpack data was collected in the twentieth century for the purpose of generating water supply forecasts. Changes in snow course conditions due to forest growth and land use changes can cause changes to appear in the time series of snow data. While the updating of regression equations can correct for this for water supply forecasting, it is more challenging to separate change in the data for these reasons from changes in the data due to climate change. As a proxy, the time series of April through July runoff volume can be used as is shown for the Sacramento River Basin in Figure 4 and the San Joaquin in Figure 5. Note that both Figures 4 and 5 show decreases in the volumes over the 20th century indicating that snowpack conditions are changing.

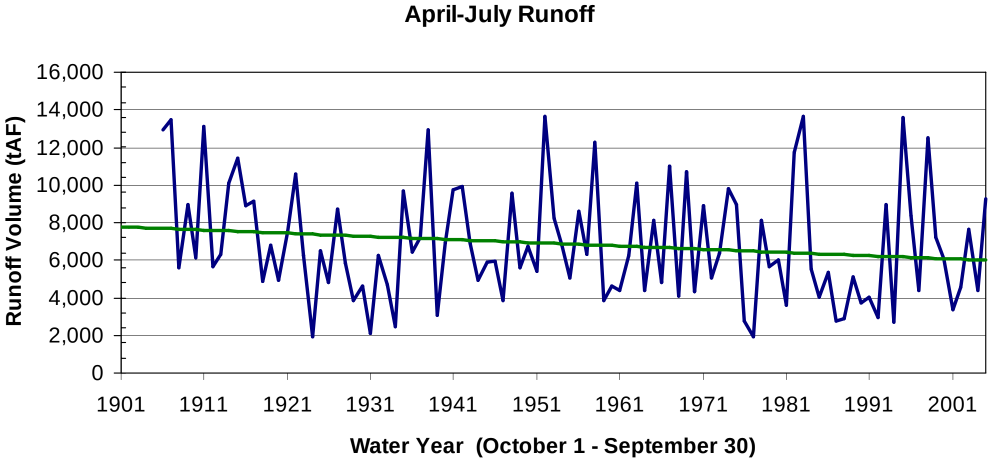


Figure 4. April through July runoff volume time series for the Sacramento River Basin

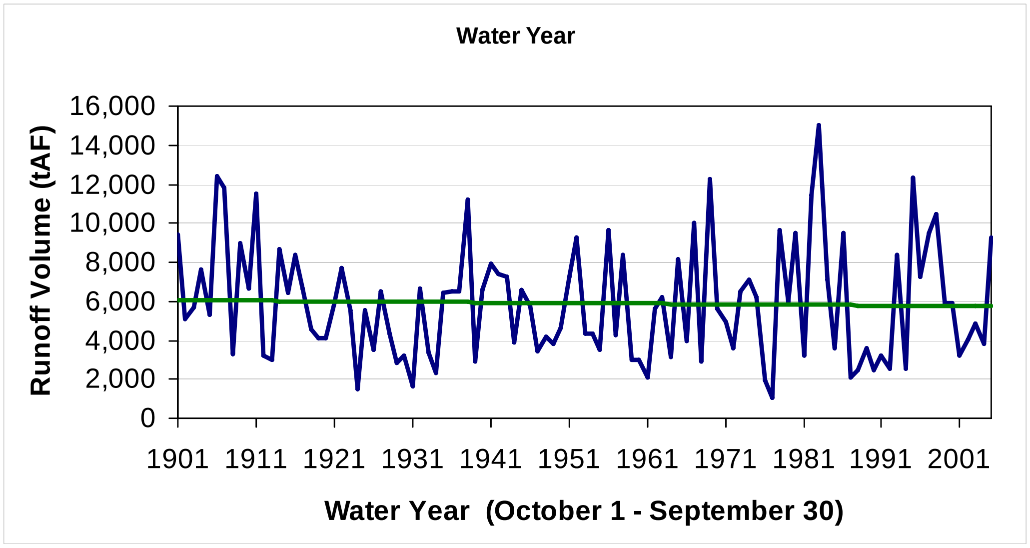


Figure 5. April through July runoff volume time series for the San Joaquin River Basin

These plots can be compared to Figures 6 and 7 which show the annual runoff volumes for the Sacramento and San Joaquin Rivers respectively. These plots show great variability but no trend indicating that the overall volume of runoff is being redistributed within the year. This can be further illustrated by examining the monthly runoff volumes for the two basins shown in Figures 8 (Sacramento) and 9 (San Joaquin). These figures show two sets of monthly runoff volume distributions corresponding to the first half and second half of the 20th century. It can be seen from these figures that winter runoff is increasing in both basins while spring runoff is decreasing. Further changes along the trends experienced in the 20th century can have significant impact and water supply and flood management practices.

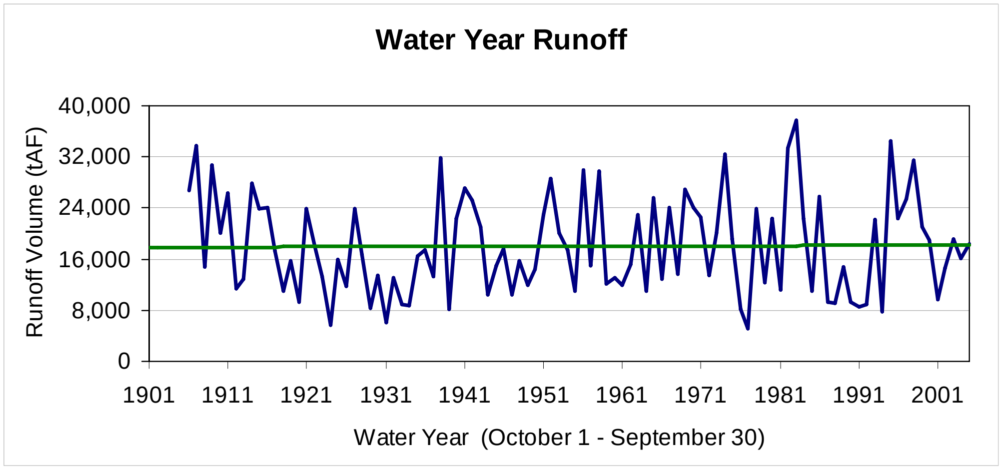


Figure 6. Annual runoff volume time series for Sacramento River Basin.

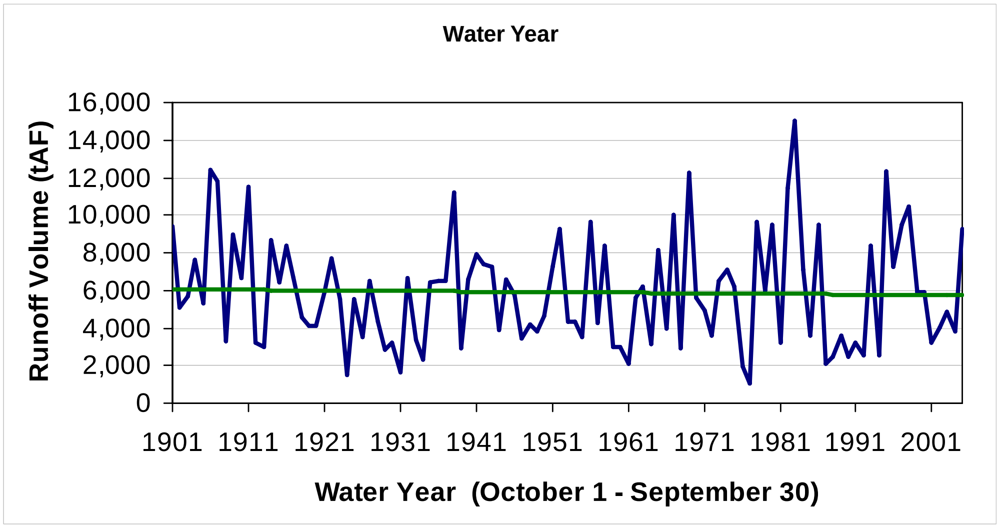


Figure 7. Annual runoff volume time series for San Joaquin Basin.

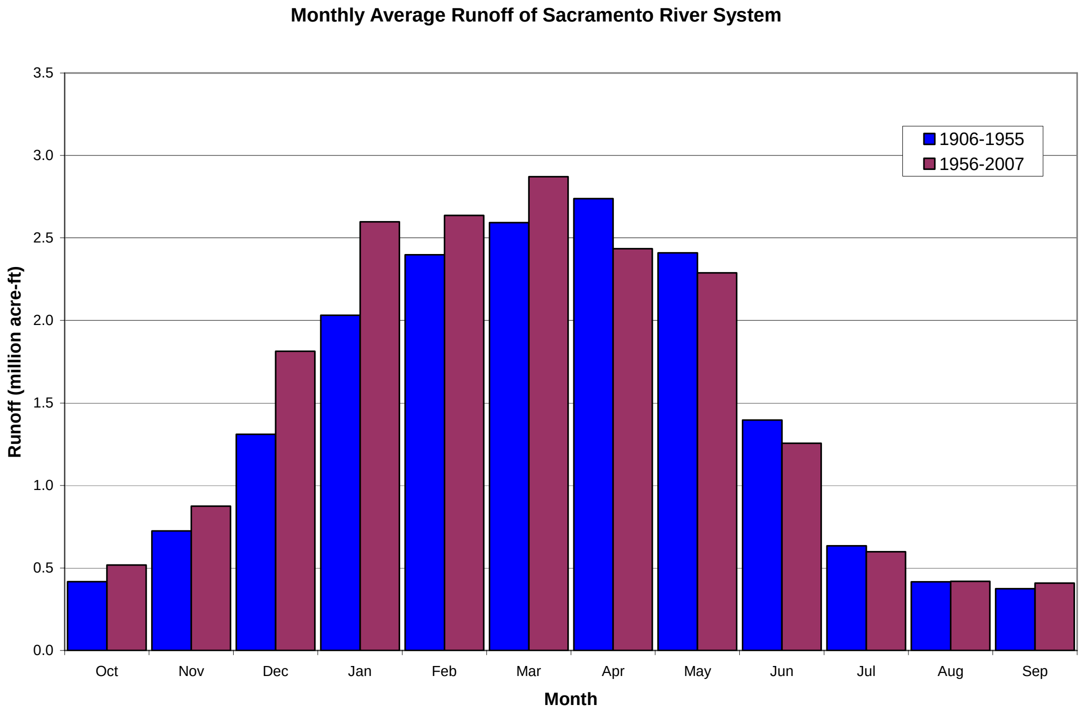


Figure 8. Monthly unimpaired runoff volumes by month for the Sacramento River.

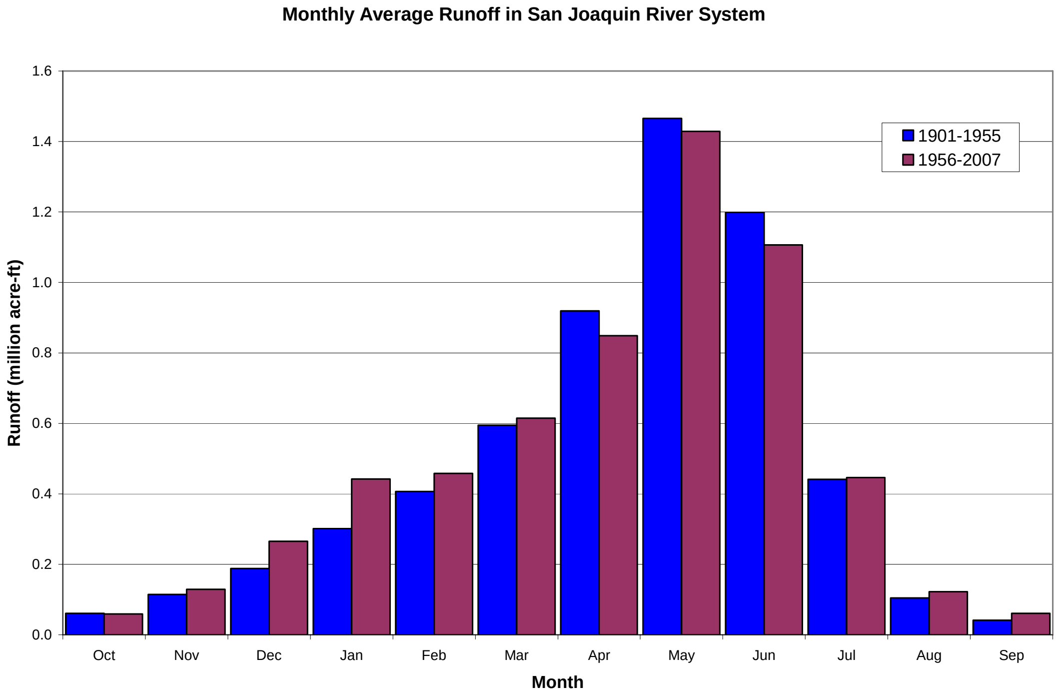


Figure 9. Monthly unimpaired runoff volumes by month for the San Joaquin River.

Peak flows are another runoff metric that has shown considerable change over the 20th century. Using data from the United States Army Corps of Engineers, the 2006 DWR report showed that the mean, standard deviation, and skew increased for the Eel, Feather, American, Tuolumne, Arroyo Seco near Soledad and the Santa Margarita Rivers. Table 5 is reproduced from Chapter 6 of the DWR 2006 report. Figure 10 shows the time series of annual maxima of 3-day average flows for the American River just above Folsom Reservoir. Note that the five largest flows greater than 100,000 cfs all occurred after 1950. These flows are substantially larger than the flows used in the design of Folsom Reservoir. With rising snow lines and the potential for larger, more intense storms the increasing trend in these statistics is expected to continue.

Table 5 - Comparison of discharge statistics by basin and time period (values in 1000 cfs)

River Basin	American	Feather	Tuolumne	Eel	Arroyo Seco	Santa Margarita
Total Period Mean	32.73	47.61	14.51	110.08	3.12	1.37
Total Period Std Dev	33.68	42.06	15.26	71.13	2.53	2.71
Total Period Skew	2.14	1.89	2.42	2.14	1.02	3.04
Pre55 Mean	28.04	42.38	12.22	92.99	3.09	1.24
Pre55 Standard Deviation	24.23	33.00	10.85	47.97	2.38	2.35
Pre55 Skew	1.76	1.38	1.72	0.47	1.03	3.51
Post55 Mean	37.00	52.23	17.20	123.26	3.09	1.42
Post55 Standard Deviation	41.00	49.68	19.33	84.18	2.71	2.93
Post 55 Skew	1.88	1.81	2.12	2.05	1.02	2.88

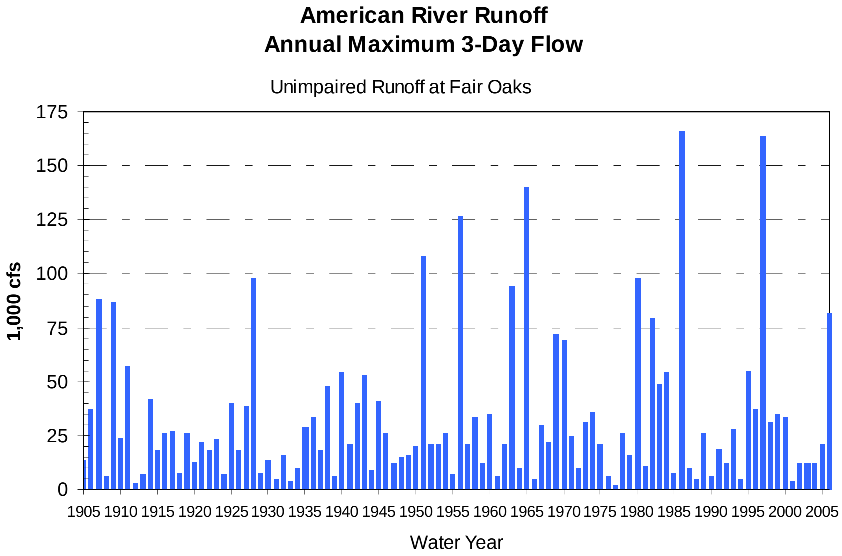


Figure 10. American River Annual Maxima of 3-day flows of unimpaired runoff at Fair Oaks.

Sea levels have been tracked via tide gages and more recently satellite (Church et al. 2006 and Beckley et al. 2007). Annual average sea level values are impacted by the number of storms that year, and tropical conditions such as El Niño or La Niña. In addition, tides go through different multi-annual cycles related to orbital paths of the Earth and Moon with respect to the Sun. In addition to these factors, land elevations can fluctuate due to tectonic activity or subsidence.

Globally, sea level has been rising during the 20th century. The IPCC 4th assessment (IPCC, 2007) estimates the rate to be approximately 0.6 feet per century with a higher rate of 0.7 feet in the last 70 years. For California, long-term sea level records are available at La Jolla, the Golden Gate, and at Crescent City. Twentieth century records of annual average sea level are shown in Fig. 11 along with a 19-year running mean. Note the local rate of rise at the Golden Gate has slowed over the last 10 years for unknown reasons. Also of note is the Crescent City time series which shows a slight decrease over the 20th century. This is likely due to tectonic activities causing land uplift in this part of the state (Roos, personal communication).

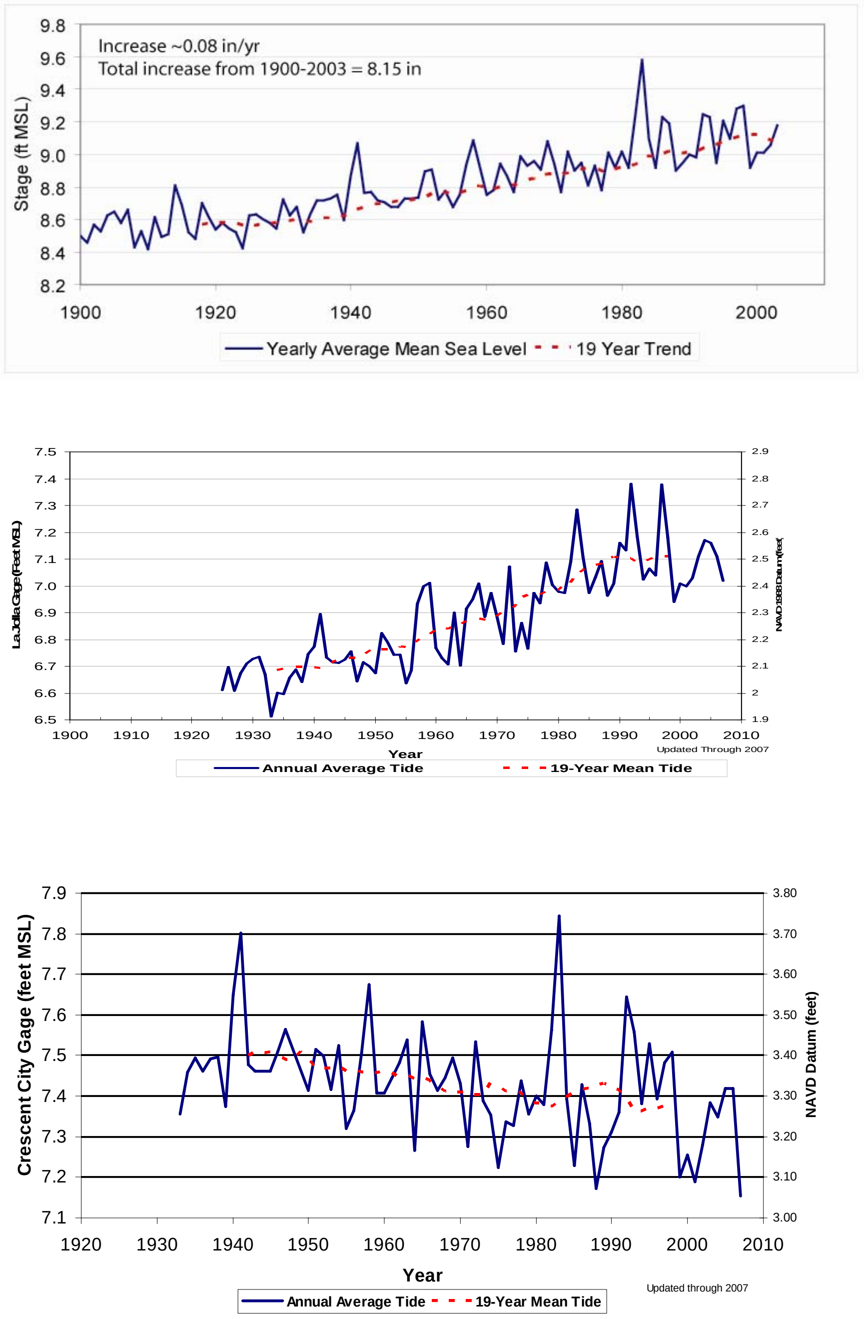
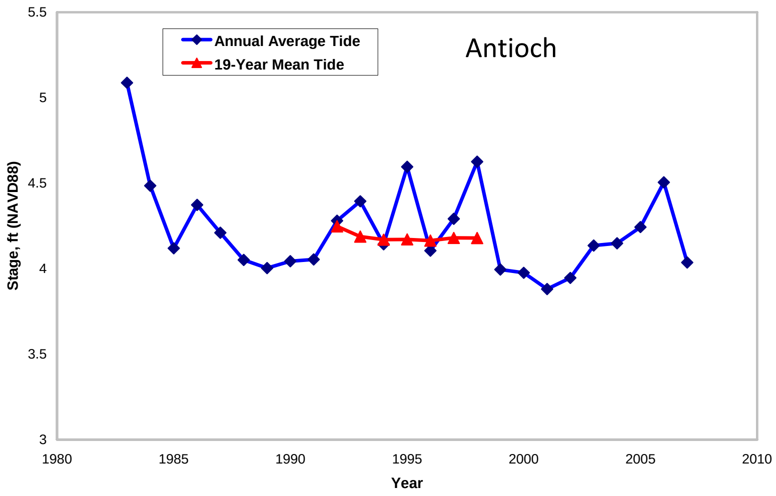
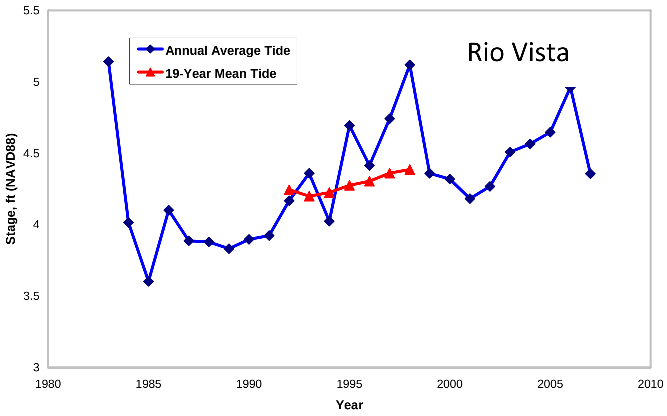


Figure 11. Twentieth century time series of annual average sea level for (a) La Jolla, (b) Golden Gate, and (c) Crescent City.

In the Sacramento/San Joaquin River Delta, referred to hereafter as the Delta, land surfaces are considered to be subsiding slowly. Although there are several tide gages in the Delta, most are on levees that are consolidating. This combination of subsidence and the historical sea level rise at the Golden Gate result in estimates of Delta sea level rise rates on the order of 0.7 feet per century. Some sample plots of historical trends in the Delta are shown in Fig. 12.





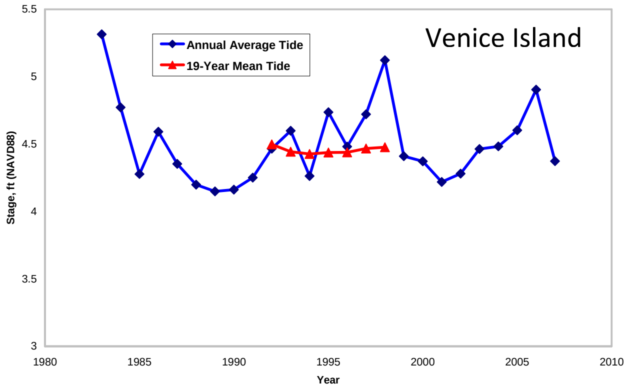


Figure 12. Plots of mean annual stage for (a) Antioch, (b) Rio Vista, and (c) Venice Island.

Satellites have been used to measure sea surface heights since 1993 via estimates of satellite altimetry. Based on this short period of record, sea level rise is estimated to be approximately 1 foot per century for the time period 1993 to 2003 (Church et al. 2006 and Beckley et al. 2007).

Paleoclimate Records – Extending the Observed Record

The climate system is complex and evolves on multiple space and time scales. Because of this, some changes or periodic fluctuations in the climate system may occur over centuries which extend beyond the observed record. One method to gain information on longer period climate fluctuations is to use proxy data like tree rings pollen, isotopes, geomorphologic features or lake sediments to reconstruct precipitation or runoff series. This effort, called paleoclimate, can provide information going back several centuries.

A review of paleoclimate methods and the data generated from them is provided in a chapter of the IPCC Fourth Assessment by Jansen et al. (2007). Woodhouse and Lukas (2008) summarize efforts that use tree-ring records to reconstruct streamflow and discuss their usefulness in water resources planning. Malamud-Roam et al., (2007) provide a synthesis of paleoclimate records for the San Francisco Bay Delta-Estuary system and point to a more comprehensive description and review of archives available made by Malamud-Roam et al. (2006).

A summary of references for paleoclimate studies in California is provided in Table 6. While tree-ring analyses are most common, several other types of paleostudies have been conducted. General descriptions of past climate states are described in some of the efforts while others develop inferred streamflow or precipitation records.

In order to facilitate the use of paleoclimate-based data and reconstructions in water resources planning and management efforts the following recommendations are put forth. First, a repository of paleoclimate data and references should be set up with a link to the repository on the California Climate Data Portal. Second a library of examples of using paleoclimate data should also be developed and made available.

Table 6 – Select Paleoclimate Study References

Study Type	References
Review	Woodhouse and Lukas (2008) Malamud-Roam et al (2007) Jansen et al. (2007) Malamud-Roam et al (2006)
Tree Rings	Meko (2001) Stahle et al. (2001) Hughs and Funkhouser (1998) Hughs and Graumlich (1996) Haston and Michaelsen (1994, 1997) Earle (1993) Scuderi (1993) Swetnam (1993) Hughes and Brown (1992)
Sediment Deposits	Roach and Cayan (2007) Field and Baumgartner (2000) Zhao et al. (2000) Mensing et al. (1999) Schimmelmann et al (1998) Sullivan (1992) Soutar and Crill (1977)
Pollen	Malamud-Roam (2002) Byrne et al. (2001) Davis (1999) Anderson and Smith (1994) Smith and Anderson (1992) Davis (1992)
Geomorphological Features	Stine (1990, 1994) LaMarche (1973, 1974)
Isotopes	Ingram et al. (1996a, b) Leavitt (1994) Ingram and DePaolo (1993)
Macrofossils	Starratt (2003, 2004) Brunelle and Anderson (2003) Gorman and Wells (2000) Anderson (1990)

Future Projections

Future projections of climate conditions are based upon computer simulations of the climate system. The computer models that are used to generate these simulations, referred to as GCMs (for General Circulation Model or Global Climate Model), are highly complex collections of atmospheric, land surface, and oceanic process equations that represent our understanding of how the physical system works. An overview of the development of GCMs for climate change research is provided in the IPCC Fourth Assessment (Le Treut et al, 2007). The review goes back to early climate modeling by Manabe and Weatherald (1975) and follows the development of models through the third IPCC assessment (IPCC, 2001). A separate chapter by Randall et al. (2007) assesses the capabilities of climate models used in the IPCC fourth assessment. Bader et al (2008) evaluates the abilities of climate models as part of the CCSP reports.

GCMs have evolved greatly since the first IPCC assessment. This evolution is depicted schematically in Figure 13. The number of processes included in the models has increased as well as the complexity of the representation of some climate processes. Spatial resolution has also improved. In addition to improved spatial resolution and dynamics and transport schemes, the current generation of GCMs now incorporates atmospheric aerosols. Advances have also been made with the depiction of ocean and sea-ice processes. Further development is expected in the areas of improving resolution, generating more realizations of simulations to generate a larger ensemble for projections, and incorporating more processes like carbon cycle feedbacks and more atmospheric chemistry (Randall et al., 2007).

The development of GCMs has benefited from more testing and Intercomparison studies. One of these studies, the World Climate Research Program Climate Model Intercomparison Project 3 (WCRP CMIP3), resulted in a multi-model dataset that is housed at Lawrence Livermore National Lab (Meehl et al., 2007). This dataset offers climate researchers a centralized location to obtain GCM simulation results.

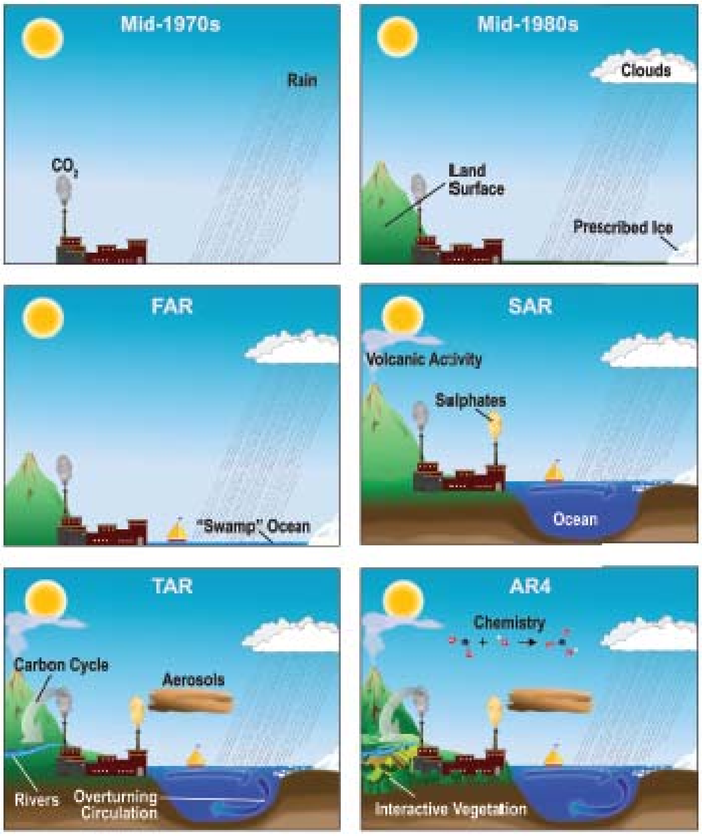


Figure 13. (from IPCC AR4 Chapter 1) Schematic of GCM capabilities with IPCC reports.

For the simulations, the scenarios are defined by the growth rate of greenhouse gas concentrations in the atmosphere. These scenarios, defined by the Intergovernmental Panel on Climate Change (IPCC, 2001), correspond to different economic and technological development assumptions. A total of 40 scenarios were developed, each of which represents an alternative interpretation and quantification of one of four storylines. The four stories are referred to as A1, A2, B1 and B2, and the major characteristics of each storyline are summarized below (IPCC, 2001):

A1: The A1 story is about a future with low population growth, rapid economic growth, and rapid introduction of new and more efficient technologies. Other characteristics of the story include convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

A2: The A2 story is about a heterogeneous future with high population growth, regional economic growth, and fragmented technological changes. Self reliance and preservation of local identities are major themes in the A2 story.

B1: The B1 story is about a convergent future with low population growth, rapid economic growth, and sustainable technology. Economic growth moves rapidly towards a service- and information-based economy. Use of natural resources is reduced, and clean and resource-efficient technologies are introduced. The B1 storyline emphasizes global solutions to economic, social, and environmental sustainability.

B2: The B2 story envisions a future with moderate population growth, intermediate levels of economic growth, and less rapid and more diverse technological development than the A1 and B1 stories. Local solutions to economic, social, and environmental sustainability are emphasized.

The four storylines reflect different directions of major greenhouse gas emissions influences, including population, technology and economic factors and evolve dynamically over time. All of the scenarios based on a given story are known as a scenario family. Of these scenarios, two have been used for studies in California – A2 and B1.

Differences in choices of how to represent certain processes in the climate system result in different projections of future conditions for a given scenario. The large number of climate models and scenarios create a wide range of future projections. Past efforts such as DWR (2006) used a bookend approach to use future projections in planning efforts. More recently, efforts such as Dettinger (2005a) have worked to take advantage of the information contained in more of the scenarios through the development of climate change distributions. Other efforts such as Brekke et al. (2007) have looked at the impact of weighting models' contributions to climate change distributions based on their ability to represent 20th century climate for California. In addition, the first analyses that develop a systematic stochastic framework for estimating future climatic uncertainty have been proposed (Koutsoyiannis et al. 2007). This is an area of ongoing research.

For the CAT assessments, 2 emission scenarios were chosen, the A2 and B1. The A2 and B1 emissions scenarios reflect possible futures with generally higher emissions (A2) and lower emissions (B1) in the 21st Century. The A2 scenario is a "storyline" of future global emissions and economic growth based on strong economic priorities (somewhat at expense of environmental priorities) and more regional than global economic coordination, but with strong emphasis on self-reliance of nations, large population increases and relatively slow economic growth overall; the result is rapid growth of greenhouse-gas emissions throughout the 21st Century. The B1 scenario reflects a possible future in which there is more global economic coordination and a stronger emphasis on environmental sustainability. Under this scenario, populations peak and stabilize, and growing economies are based more on services and information. The result is that emissions during the 21st Century are less than under A2, although most of the differences in the emissions emerge after about 2050.

For the second biennial assessment of potential climate change impacts in the State, the CAT has chosen a set of climate-change scenarios derived from six global climate models shown in Table 7. Two of these six models were the models used for the first CAT assessment.

Table 7 - GCMs used in 1st and 2nd CAT reports

No.	GCM used in the 2008 report	GCM used in the 2006 report	Country
1	CNRM-CM3		France
2	GFDL-CM21	GFDL-CM21	USA
3	MIROC32med		Japan
4	MPI-ECHAM5		Germany
5	NCAR-CCSM3		USA
6	NCAR-PCM1	NCAR-PCM1	USA

These models were chosen on the basis of the availability of detailed output data for use in various parts of the assessment process and upon consideration of certain aspects of their performance. The availability of daily simulation output of surface-air temperatures and precipitation were required so that the scenarios could be used to drive hydrologic models over the State. Sub-daily output data were also valued for use in coastal wave models and sea-level projections. Data was obtained via the model centers and not just from the Intergovernmental Panel on Climate Change (IPCC) web pages, to acquire the most recent data and more complete data in many cases.

Models were assessed in terms of their abilities to reproduce El Nino-Southern Oscillation (ENSO)-like climate variations and their tendency to produce periods of drought over California. Models needed to yield reasonably realistic annual cycles of monthly temperature and precipitation over California. The models chosen also had to perform on reasonably detailed global grids. Finally models chosen had to provide historical and future climate simulations under specific greenhouse-gas emissions scenarios, so that all the model outputs could be directly compared. In some cases, models were chosen based on recommendations of the model development group, or because they possessed better documented than alternatives. Further detail on the models can be found at http://meteora.ucsd.edu/cap/ipcc4.html.

With two emissions scenarios and six climate models, a total of 12 climate-change scenarios are at the focus of the 2008 assessment activities. A summary of the precipitation and temperature projections from the GCMs are provided here. Projections for runoff, snowpack, and sea level change all require additional modeling based off of the GCM results and are presented in a later section.

GCM results, in general, lack the detail and spatial resolution needed for water resources planning and management. In order to obtain the needed resolution, a process known as downscaling must be carried out. Downscaling can be carried out using a statistical basis, a dynamical basis, or some combination of the two. The statistical and dynamical bases for downscaling are reviewed here and efforts carried out for California using these methodologies are cited. A schematic of the process is shown in Figure 14.

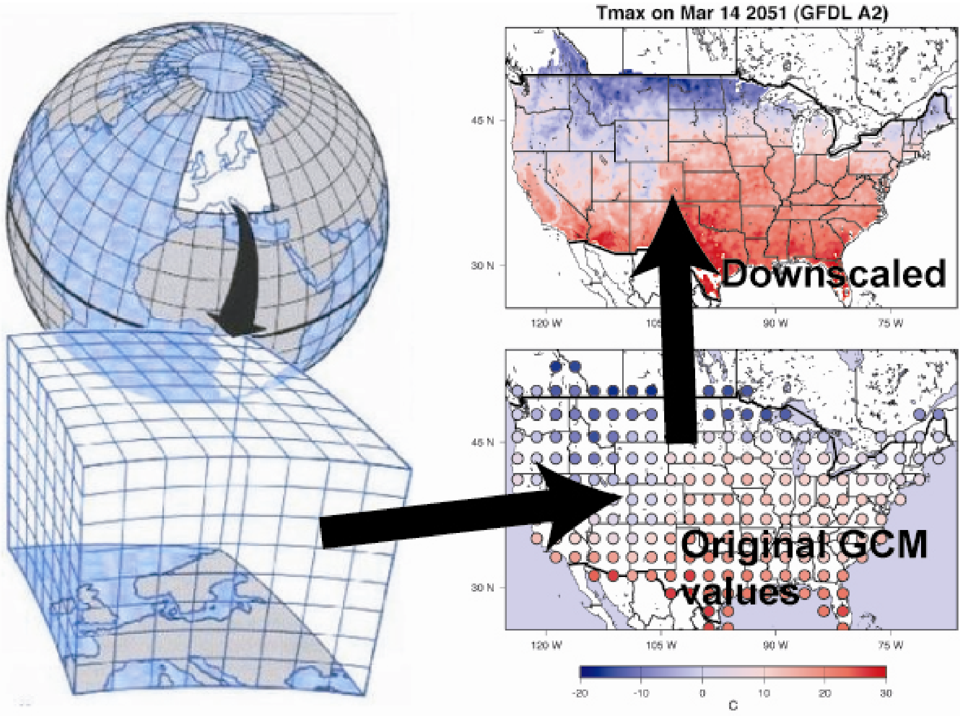


Figure 14. Schematic of downscaling process (from M. Dettinger.)

Statistical downscaling uses spatial relations and transfer functions based on historical data to interpolate GCM data to a finer resolution. Two methods have recently been developed and used to produce collections of downscaled GCM data for California: The Bias Correction and Statistical Disaggregation (BCSD, Wood et. al 2004, and Maurer,

2007) and Constructed Analogs (CA, Hidalgo et al, 2008). A comparison of the methods is provided in Maurer and Hidalgo (2008).

The BCSD method is a two-step process that first removes biases from the GCM projections before downscaling using projection factors and monthly mean fine-scale grids for temperature and precipitation. This method has been applied to 112 projections based on 16 GCMs and 3 emission scenarios that are part of the WRCP CMIP3 multi-model dataset. These downscaled projections are available for the contiguous United States and can be retrieved online as part of a Santa Clara University and United States Bureau of Reclamation Project (Maurer et al., 2007).

The CA method uses historical patterns as analogs for the downscaling process. Four steps are used with this method. The first step compiles a library of fine-grid historical data and aggregates this data to a coarse GCM grid. A subset of these grids that show a meteorological pattern similar to the future projection is chosen. A linear regression of the candidate grids to match the future projection is constructed creating the constructed analog. The same regression pattern is then applied to the fine-scale grids to create the downscaled data.

The BCSD approach was applied to the outputs of all the six GCM simulations under both emission scenarios, thus resulting in twelve cases. The CA downscaling approach was applied to the outputs of three GCM (CNRM-CM3, GFDL-CM21, and NCAR-PCM1) simulations under both emission scenarios, resulting in an additional six cases. These 18 cases were used in DWR assessments associated with the CAT second assessment.

Dynamical downscaling uses computer simulations of the climate system over a limited spatial area at finer resolution to generate the fine-scale climate change data. The GCM data is used as boundary conditions for the finer-scale model. Dynamical downscaling is more computationally intensive than statistical downscaling, but can produce more information for use in subsequent water resources studies. Anderson et al. (2005) created a 3-km resoluion downscaled hydroclimate dataset of reanalysis data for water resources studies in the Lake Tahoe Basin. Kanamitsu and Kanamaru (2007) and Kanamaru and Kanamitsu (2007) describe a 57-year downscaling of reanalysis data for the state of California at 10-km resolution. Georgakakos et al. (2007) used an orographic precipitation model coupled to a boundary layer procedure for estimating mutually consistent precipitation and temperature. The model is used in the context of demonstrating the benefits of integrated climate-hydrology forecasts and reservoir management in Northern California, and most recently is being applied to downscale sub-daily resolution GCM output for this region for developing adaptation strategies for Northern California. Dynamical downscaling was not used for DWR assessments associated with the CAT second assessment and is still an area of active research.

Conclusions – Where we are and Moving Forward

Climate change science provides an abundance of information for water managers. Unfortunately, the information is located in a myriad of locations and in forms that may not be readily useful in water resources operations, planning and management applications. California is fortunate to have the California Energy Commission's PIER program to move California climate change research forward and to connect climate change research to water resources management. This effort provides a useful conduit for the exchange of ideas.

Currently California possesses a wide range of observing networks, many of which were not designed to monitor for climate change. An evaluation of the existing networks and needed modifications for climate change monitoring is needed.

Paleoclimate studies offer insight into periods with greater climate variability and can provide realistic scenarios for water resources planning and management. Examples of water resources applications and a central repository of paleoclimate records for California water resources studies are needed.

In the coming years California will be developing adaptation strategies to cope with climate change impacts. For the water resources community, further refinement of planning and management tools to incorporate climate change data will facilitate the development of adaptation strategies. These strategies should reflect the relative risk of different climate change impacts for different local regions of California.

Acknowledgements

The author wishes to thank the following people for assisting in the preparation of this article: Michael Dettinger, Jamie Anderson, Maury Roos, Kelly Redmond, Frank Gerhke, Connie Millar, Bob Westphal, Kevin Kuo

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