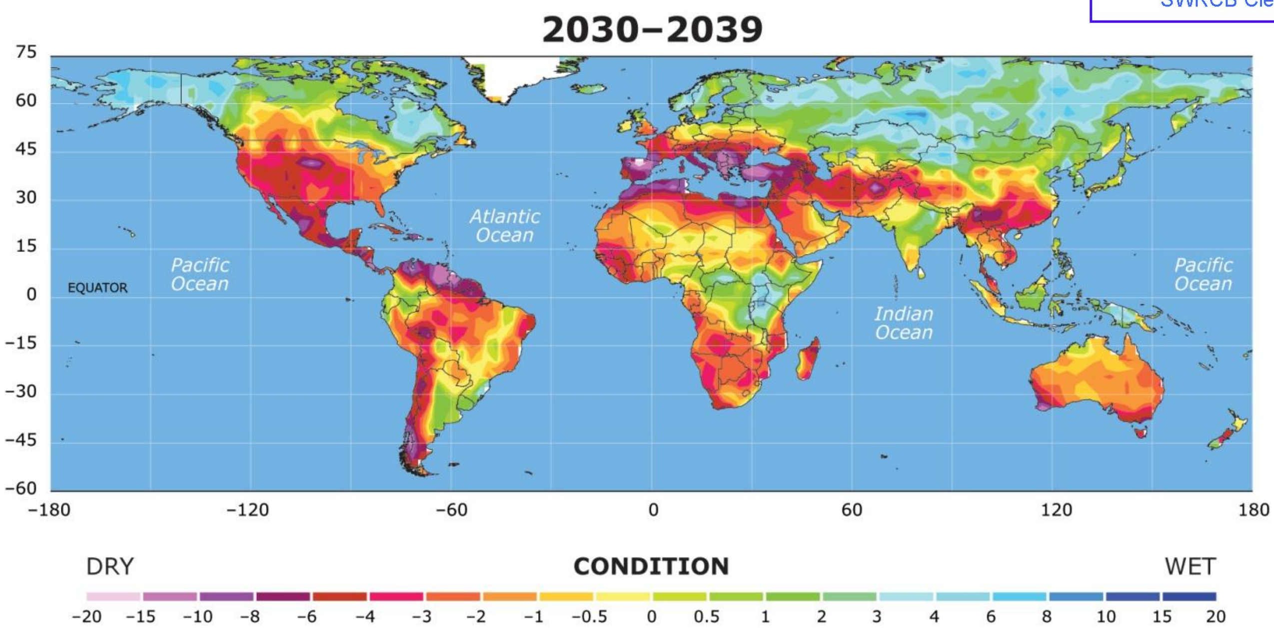
CALIFORNIA WATER RESEARCH



Incorporating Drought Risk From Climate Change Into California Water Planning

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Introduction

The Worldwide Drought

Recent years have seen exceptionally severe droughts in the United States, and across the world. The droughts have been exceptional for the combination of record heat and reduced precipitation, and some for unprecedented length. The recent record drought in the Southwest has also affected northern Mexico, and caused a 40% drop in agricultural production in that country.[1] There has also been exceptional drought in the Southeast, affecting southern Georgia from 2010-2012[2] and spreading to North Carolina this year.[3] A severe drought in the Midwest developed this year, which has extended into central and eastern Canada.[4]

1The Rio Negro, the largest tributary to the Amazon, in 2010

Photo by Raimundo Valentim/EPA/CORBIS

In South America, the Rio Negro, the largest tributary to the Amazon, dried up in 2010.[5] In 2012, rivers have dried up in northeastern Brazil, threatening the water supplies for 1,100 towns.[6] Argentina has seen two record droughts in four years, hurting soybean and corn crops.[7]

In Europe, Spain and Portugal are now facing the worst drought in 70 years,[8] and Russia saw a record drought in 2010, which caused the country to ban exports of grain.[9] Russia is experiencing another drought this year.[10]

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[1] Drought Reduces Mexico's Agricultural Production by 40%, Latin American Herald Tribune, February 2012. Available at http://www.laht.com/article.asp?CategoryId=14091&ArticleId=470584

[2] Special Report: South Georgia's Drought, WALB News ABC 10, February 20, 2012. Available at http://www.walb.com/story/16975753/special-report-south-georgias-drought

[3] Southeast Drought 2012: Georgia, South Carolina Residents Try To Make Do With Dry Weather, Jeffrey Collins, Associated Press, May 29, 2012. Available at http://www.huffingtonpost.com/2012/05/29/southeast-drought-2012-ga-sc-fl-nc_n_1552516.html

[4] Drought in Central, Eastern Canada baking crops: Weather a 'double whammy,' expert says. CBC News Canada, July 15, 2012. Available at http://www.cbc.ca/news/canada/story/2012/07/15/canada-hot-weather-lack-of-rain.html

[5] Drought brings Amazon tributary to lowest level in a century, Eric Laczi, The Amazon Rainforest Blog, October 26, 2010. Available at http://theamazonforest.blogspot.com/2010/10/drought-brings-amazon-tributary-to.html

[6] Worst drought in 50 years takes toll in northern Brazil. AFP, May 13, 2012. Available at http://www.google.com/hostednews/afp/article/ALeqM5hF2YL3XXHgebFiB6FQ91QnS-2qkw?docId=CNG.605297c60c7fe4592c03dee29f28e996.cc1

[7] Argentine Drought May Be Worst For Crops In Over 70 Years, Laura Price, Bloomberg News, Jan 6, 2012. Available at http://www.bloomberg.com/news/2012-01-06/argentine-drought-may-be-worst-for-crops-in-more-than-70-years.html

[8] Spain, Portugal face worst drought in 70 years, Daniel Woolls, Associated Press, March 15, 2012. Published in The Star (Canada). Available at http://www.thestar.com/news/world/article/1146764--spain-portugal-face-worst-drought-in-70-years

[9] Russia Suffers Severe Heat, Drought. Jim Andrews, Senior Meterologist, AccuWeather.com, July 14, 2010. Available at http://www.accuweather.com/en/weather-news/russia-suffers-severe-heat-dro/33994

[10] Russia Drought Cuts Wheat Production, Reuters, August 8, 2012. Available at http://www.agprofessional.com/resource-centers/wheat/news/Russia-drought-cuts-wheat-production-165442056.html

In Asia, China has seen a record drought from 2010-2012, which affected 6.3 million people, and dried up the Yangtze River in 2011, forcing the release of 4.5 maf of water from upstream dams.[11] India is seeing its second drought in four years, and rain in the Punjab region is 70% below average.[12] In East Africa, "the worst drought in 60 years" caused a food crisis in 2011 in Somalia, Ethiopia, Djibouti, and Kenya, and threatened the lives of 9.5 million people.[13] In southwestern Australia, a twelve year drought was declared as "without historical precedent."[14]

Drought and Climate Change

The unprecedented severity of recent droughts has been linked to climate change by numerous studies. The 2007 IPCC summary for policy makers stated in part,

> More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation have contributed to changes in drought. Changes in sea surface temperatures (SST), wind patterns, and decreased snowpack and snow cover have also been linked to droughts.[15]

In California, several recent climate change impact studies have predicted increased frequency and severity of droughts, as well as markedly reduced stream flow and reduced reservoir inflows. The results from these studies should be incorporated into modeling and planning by the Department of Water Resources.

In addition, prior modeling by the Department of Water Resources to assess climate change impacts on the State Water Project and Central Valley Project has used techniques which map downscaled global climate model output onto the historical record of wet and dry years. These techniques lose a great deal of information about changes in drought frequency and persistence under climate change. A 2010 analysis of modeling of climate change in DWR planning studies, noted:

> there is a lack of analysis of potential drought conditions that are more extreme than have been seen in our relatively short hydrologic record. There is significant evidence to suggest that California has historically been subject to very severe droughts and that climate change could result in droughts being more common, longer, or more severe. However, most current DWR approaches rely on an 82-year historical hydrologic record (1922–2003) on which GCM-

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[11] China crisis over Yangtze river drought forces drastic dam measures: Severe drought has forced China to release 5bn cubic metres from Three Gorges reservoir for irrigation and drinking water. Jonathan Watts, Asia environment correspondent, UK Guardian, May 25, 2011. Available at http://www.guardian.co.uk/environment/2011/may/25/china-drought-crisis-yangtze-dam

[12] India's Drought Highlights Challenges of Climate Change Adaptation, Robert Eshelman and ClimateWire, August 3, 2012. Available at http://www.scientificamerican.com/article.cfm?id=indias-drought-highlights-challenges-climate-change-adaptation

[13] 2011 East Africa Drought, Wikipedia. Available at http://en.wikipedia.org/wiki/2011_East_Africa_drought

[14] Longest, hottest drought on record, says Bureau of Meteorology. Asa Wahlquist, The Australian. October 11, 2008. Available at http://www.theaustralian.com.au/news/health-science/longest-hottest-drought-on-record/story-e6frg8gf-1111117721981.

[15] IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., p. 9. Available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

> generated future climate changed-hydrologic conditions are superposed. This record is likely too short to incorporate the possibility of a low frequency, but extreme, drought.[16]

Full consideration of drought risks due to climate change and needed adaptations are essential in water resource planning. Therefore the Climate Change Adaptation Strategy for the Department of Water Resources needs to use all available information about increased drought risk due to climate change, re-evaluate prior studies on climate impacts to the State Water Project and Central Valley Project to incorporate this information, and consider strategies for reducing risk of interruption of water supplies.

Recommendations

We make the following recommendations for the California Climate Adaptation Strategy on water:

1. When evaluating Global Climate Models for application to California water resources planning, the Department of Water Resources should consider the drought-related effects mentioned in the 2007 IPCC report. DWR should also consider the accuracy of GCMs in predicting the recent, prolonged drought in the Southwest region and other areas affected by the El Nino / Southern Oscillation. (ENSO).

2. Comparison of Global Climate Model outputs with California's precipitation record should look not only at precipitation trends for the entire state, but also at regional records, which show drying in Southern California.

3. Studies from the 2009 and 2012 California Climate Change Assessments, projecting increased frequency and severity of droughts in California, should be evaluated and relevant information should be incorporated into future planning and modeling by the Department of Water Resources.

4. Previous modeling by DWR, which uses mapping onto the historic hydrology, should be re-evaluated with respect to risks of increased frequency and severity of droughts. This includes modeling of future stream flows and reservoir inflows used in the 2009 Climate Adaptation Strategy Assessment, and the 2009 and 2011 State Water Project Reliability Reports.

5. Model projections under higher greenhouse gas emissions scenarios tend to be drier. These scenarios are also more likely, given current trends. Whenever possible, information about higher GHG scenarios should be provided separately in planning studies, so that shifts under higher GHG scenarios can be assessed.

6. The method of quantile mapping of climate change models, which has been used in BDCP modeling, implicitly assumes that wetter and drier futures are equally likely. This assumption should be re-examined in light of new knowledge about global climate models and the impacts of climate change on drought frequency and severity around the world. In addition, when quantile mapping is used, the projections of the wetter and drier ensembles should be provided separately so that the range of potential climate change impacts can be assessed.

[16] Climate Change Characterization and Analysis in California Water Resources Planning Studies, Final Report, Abdul Khan and Andrew Schwarz. Department of Water Resources December 2010, p. xvi. Available at http://www.water.ca.gov/climatechange/docs/DWR_CCCStudy_FinalReport_Dec23.pdf

7. Whenever possible, ensemble modelling should include information about the range of predictions by individual models. This provides information about the degree of uncertainty in the ensemble projections.

8. Water planning and evaluation of future water project operations should consider not only total water deliveries, but risk taken in deliveries, particularly with respect to carryover storage.

9. Information about drought risk to State Water Project deliveries should be summarized and provided to water agencies for inclusion in updates to Integrated Regional Water Management Plans.

10. Information about environmental risk from increased frequency and severity of droughts should be incorporated into environmental evaluations of proposed projects and proposed changes in long-term operations, including studies for CEQA / NEPA, FESA/CESA, and HCPs and NCCPs.

The following sections elaborate on the recommendations, citing recent research.

Discussion of Recommendations

1. When evaluating Global Climate Models for application to California water resources planning, the Department of Water Resources should consider the drought-related effects mentioned in the 2007 IPCC report. DWR should also consider the accuracy of GCMs in predicting the recent, prolonged drought in the Southwest region and other areas affected by the El Nino / Southern Oscillation. (ENSO).

The table below, from the Department of Water Resources, shows the models used in the 2009 and 2012 California Climate Change Assessments.

No.	Model name; modeling group, country	Model identification	Primary reference year
1	Parallel Climate Model; National Center for Atmospheric Research (NCAR), USA	PCM	2000
2	Geophysical Dynamics Laboratory model version 2.1; US Dept. of Commerce / National Oceanic and Atmospheric Administration (NOAA) / Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-CM2.1	2006
3	Community Climate System Model; National Center for Atmospheric Research (NCAR), USA	CCSM3	2006
4	Max Planck Institute (MPI) for Meteorology, Germany	ECHAM5/ MPI-OM	2006
5	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	2004
6	Meteo-France / Centre National de Recherches Meteorologiques (CNRM), France	CNRM-CM3	2005

(CAT, 2009 and Randall et al., 2007)

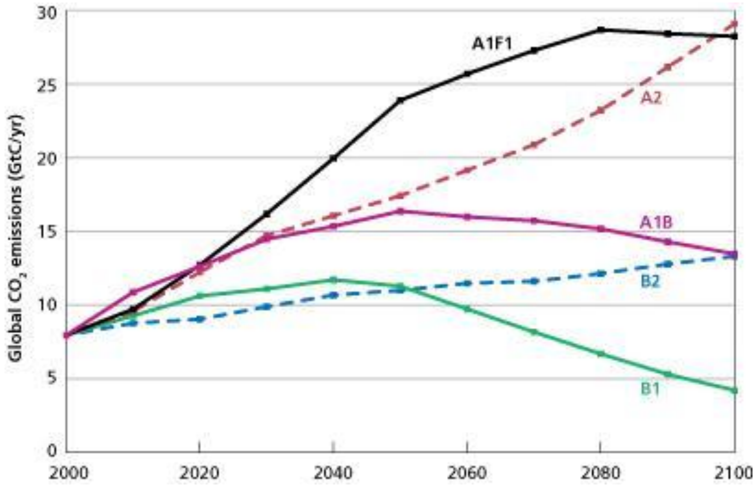
2 **Table of models used in 2009 California Climate Change Assessment Source: Department of Water Resources.**

The models were chosen

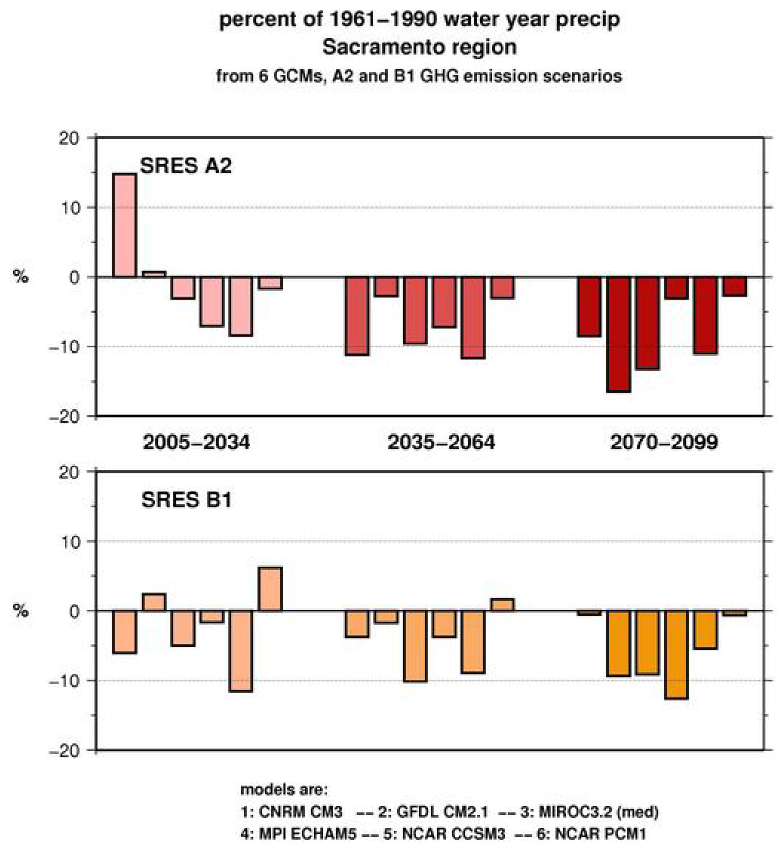
> "on the basis of providing a set of relevant monthly, and in some cases daily, data. Another rationale was that the models provided a reasonable representation, from their historical simulation, of the following elements: seasonal precipitation and temperature (Figure 1), the variability of annual precipitation, and El Niño/Southern Oscillation (ENSO)."[17]

[17] Climate Change Scenarios And Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, A Paper From the California Climate Change Center. Dan Cayan, Mary Tyree, Mike Dettinger, Hugo Hidalgo, Tapash Das, Ed Maurer, Peter Bromirski, Nicholas Graham, and Reinhard Flick. Available at http://www.energy.ca.gov/2009publications/CEC-500-2009-014/CEC-500-2009-014-F.PDF

The graph below shows C02 emissions under the IPCC Special Report on Emissions Scenarios. For the 2006 Climate Change Assessment, the Climate Action Team chose two greenhouse gas emissions scenarios rom.for modeling, the A2 (medium-high) scenario, and the B1 (low) scenario., based on availability of data. These scenarios were also used for the 2009 and 2012 Climate Change Assessments.



The projections of changes in precipitation in Sacramento from the 2009 Climate Assessment are shown below. Four of the Global Climate Models project less precipitation for the current period (2005-2034) under the A2 (medium-high) scenario, as well as four under the B1 (low) scenario. By 2035-2064, all six Global Climate Models predict less precipitation under the A2 scenario, and four of the six predict significantly less.



3 Predictions of change in precipitation at Sacramento for 6 Global Climate models

Source: 2009 California Climate Change Assessment

Discussions of climate modeling in California frequently mention that the state experiences a great deal of natural variability in precipitation from fluctuations in sea surface temperatures, including the El Nino / Southern Oscillation (ENSO) and the Pacific Decadal Oscillation.

Looking at how climate change may have affected recent droughts in the Southwest and in Australia gives more information. These regions experience similar climactic variability from the ENSO. While the 2011 drought in Texas was strongly influenced by the La Nina phase of the ENSO, Rupp and Mote found that global warming could be decreasing the return period for low precipitation events, and that heat waves are now 20 times more likely when compared with similar large-scale weather patterns in the 1960s.[18] Karoly, Risbey, and Reynolds also thought the combination of low precipitation and record heat was contributed to the severity of the unprecedented drought in Australia, and was related to climate change.[19]

[18] David Rupp and Phillip Mote et.al. Did Human Influence On Climate Make The 2011 Texas Drought More Probable? In Explaining Extreme Events of 2011 From A Climate Perspective, Thomas Peterson, Peter Stott And Stephanie Herring, Editors. Published in the Journal of the American Meterological Society, July 2012. Available at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00021.1

[19] Global Warming Contributes to Australia's Worst Drought. David Karoly, James Risbey, and Anna Reynolds. World Wildlife Fund Australia, January 14, 2003. Available at http://qualenergia.it/UserFiles/Files/Cl_IC_EE_03_Global_Warming_2003.pdf

It has also been noted that ocean warming can cause climate signals from ocean temperaturs to act synergistically. In 2003, Hoerling and Kumar discussed the dynamics behind the 1998-2002 droughts spanned the United States, southern Europe, and southwest Asia. These droughts were associated with persistently warm sea surface temperatures in the western tropical Pacific and Indian Oceans for these years, as well as cold temperatures in the eastern tropical Pacific. The climate signals acted synergistically, contributing to widespread mid-latitude drying and creating a widespread, mid-latitude drought. They noted that the scenario was ideal for a spatially expansive, synchronized drought. [20]

In sum, while there is a great deal of variability of precipitation in California due to the El Nino / Southern Oscillation and the Pacific Decadal Oscillation, global warming appears to be affecting both the oscillations, and their resulting climate impacts. Recent droughts in the Southwest and Australia show that global climate models may have important information about these changes.

The global climate models chosen for 2009 and 2012 California Climate Assessments were chosen in part for reproducing the ENSO variability. Five of the six models predicted an increased precipitation minus evapotranspiration anomaly in the Southwest, indicating a shift towards a more arid climate.[21] The exception was the National Center for Atmospheric Research Parallel Climate Model (PCM), which predicts such a shift much later in the 21st Century. The PCM model is also the only one of the six models to show a trend of increasing precipitation in California the near term and at mid-century.

2. Comparison of Global Climate Model outputs with California's precipitation record should look not only at precipitation trends for the entire state, but also at regional records, which show drying in Southern California.

Discussions of climate modeling in California also mention that the set of Global Climate Models chosen for the 2009 and 2012 Climate Change Assessment are drier than current precipitation trends in the state, which shows a slight increase overall.

Looking at regional precipitation in California gives a more complete picture. As noted by Killam and Bui et. al., examination of regional data shows a marked decline in precipitation in Southern California since 1975, a slight decline in the San Joaquin Valley and a slight increase in Northern California, with a large increase on the North Coast.[22],[23]

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[20] The Perfect Ocean for Drought, Martin Hoerling and Arun Kumar, Science, Vol. 299 no. 5607, pp. 691-694 January 31 2003. Available at http://www.sciencemag.org/content/299/5607/691.short

[21] Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, Richard Seager, Mingfang Ting, Isaac Held, et. al., Science, Vol 316 no. 5828 p. 1181-1184, May 25, 2007. Available at http://www.sciencemag.org/content/316/5828/1181.short

[22] Killam, D., A. Bui, S. LaDochy, P. Ramirez, W. Patzert and J. Willis. 2011. Precipitation trends in California: Northern and central regions wetter, southern regions drier. Unpublished. Cited in Temperature and precipitation trends in California: Global warming and Pacific Ocean influences, LaDochy and Ramirez et. al. (See reference 20.)

[23] Regional precipitation data with linear trends also available from Western Regional Climate Center, California Climate Tracker. Available at http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html

Mean precipitation Linear trends/ 100 yrs	N Central	N Coast	NE	Sierra	Sac Delta	Central Coast
1895-present	+247.9	-21.1	+52.1	+114.6	+128.8	+77.7
1949-present	-75.9	-219.7	-67.3	-8.1	+61.0	+82.3
1975-present	+98.8	+479.6	-31.5	-74.2	+26.9	+71.6
	San Joaquin	S. Coast	S. Interior	Mojave	Sonora	
1895-present	+36.6	+88.1	-10.2	+39.9	+24.1	
1949-present	+50.3	+75.7	+28.4	+57.9	+43.4	
1975-present	-135.4	-340.4	-642.4	-205.2	-245.1	

4 Annual Precipitation linear trend in mm/100 years. From Killam et. al.

La Dochy and Ramirez, et. al. suggested that the precipitation decrease in Southern California may be due to a northward shift in the storm track position in the West in later winter and early spring, and that the subtropical anticyclone belt may also shifting northward.[24] Such a shift has also been observed in global climate change models, and Seager et. al. conjectured that it was associated with the recent severe drought in the Southwest.[25]

The shifts are in agreement with projections by the large ensemble of 112 GCM / scenario combinations used by the U.S. Bureau of Reclamation for the 2011 Westwide Climate Risk Assessment.[26] The ensemble median projected drying in Southern California and the Central Sierras by mid-century, as well as drying across the Southwest. By the 2070s, the ensemble median projected drying throughout California.

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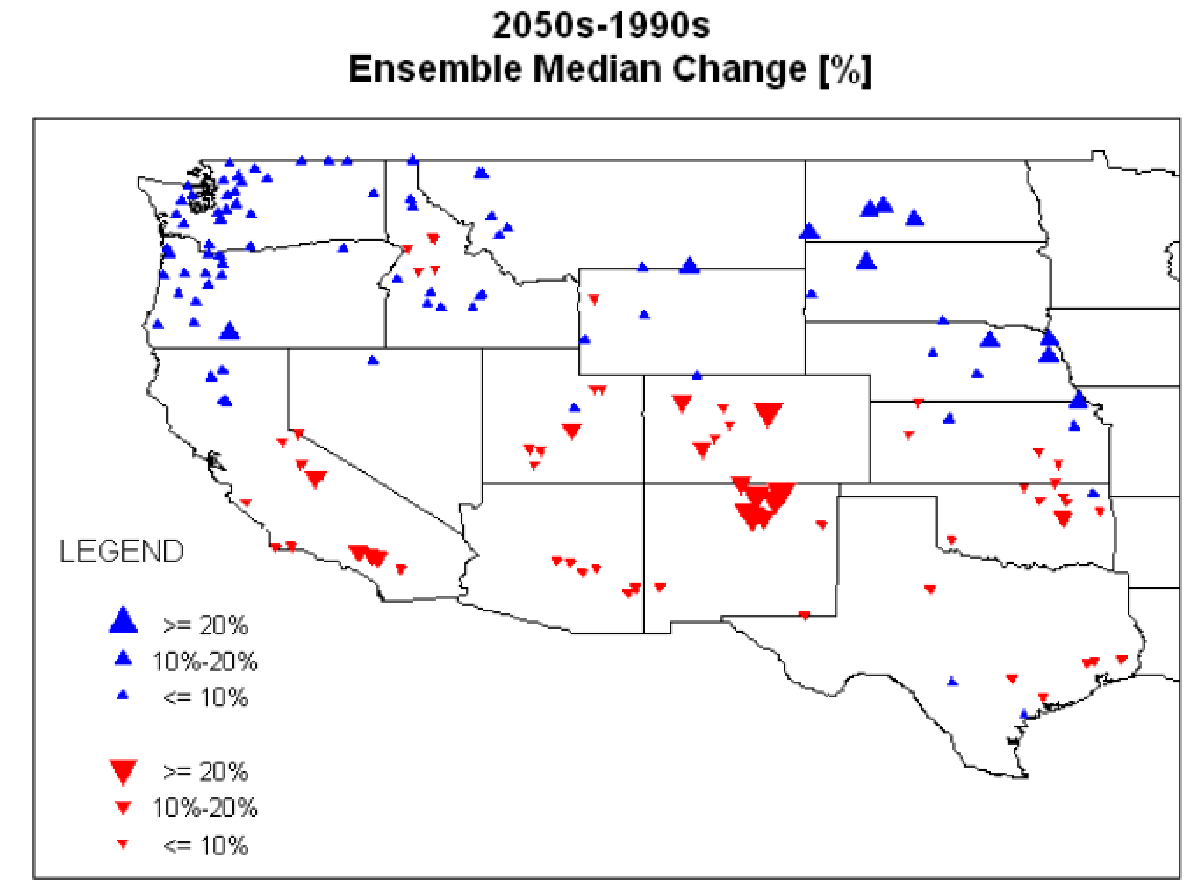
[24] Temperature and precipitation trends in California: Global warming and Pacific Ocean influences. Steve LaDochy, Pedro Ramire1, Dan Killam, Ann Bui, William Patzert and Josh Willis. AMS Climate extended abstract. Available at https://ams.confex.com/ams/91Annual/webprogram/Manuscript/Paper177504/AMS%20climate%20Extended%20abstract-pedro(2).pdf

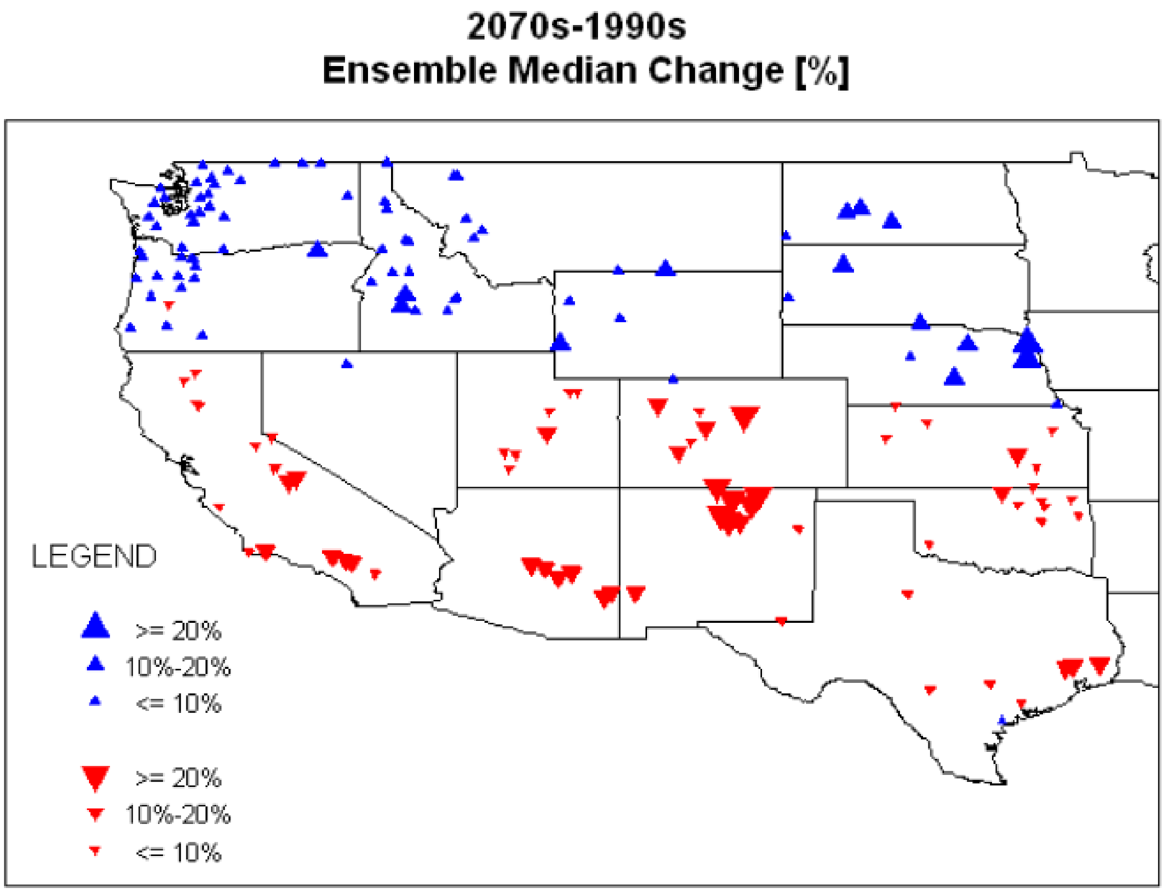
[25] Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, Seager et. al., op. cit.

[26] West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections, U.S. Department of the Interior Bureau of Reclamation Technical Memorandum No. 86-68210-2011-01, March 2011. Available at http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf



5 **Median projected changes in annual precipitation from ensemble of 112 GCM / scenario combinations, mid-century**

Source: US Bureau of Reclamation, West-wide Climate Risk Assessment, 2011.



6 Median projected changes in annual precipitation from ensemble of 112 GCM / scenario combinations end of century
Source: US Bureau of Reclamation, West-wide Climate Risk Assessment, 2011.

3. Studies from the 2009 and 2012 California Climate Change Assessments, projecting increased frequency and severity of droughts in California, should be evaluated and relevant information should be incorporated into future planning and modeling by the Department of Water Resources.

There are now enough studies of impacts of climate change on frequency of droughts in California for the Department of Water Resources to include potential increases in frequency of dry and critically dry years in planning and modeling. An assessment of possible increase in drought risk is essential for reliability planning for the State Water Project and the urban water agencies which contract with the State Water Project.

We describe two recent studies below, which were sponsored by the California Climate Change Center and released in support of the 2012 and 2009 California Climate Change Assessments.

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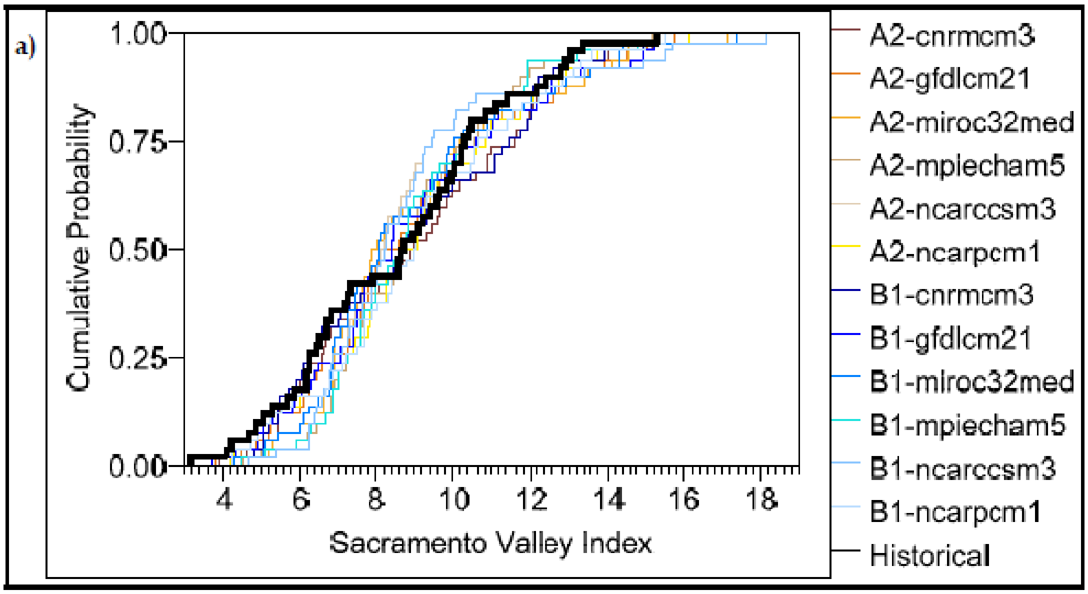
A. Water and Energy Sector Vulnerability to Climate Warming in the Sierra Nevada: Water Year Classification in Non-Stationary Climates, July 31, 2012.

As part of the 3rd California Climate Change Assessment in 2012, the California Climate Change Center released this study by Sarah Null and Josh Viers at UC Davis.

The study used the six global climate models from the second California Climate Assessment, and made projections under the SRES A2 (medium-high) and B1 (low) greenhouse gas emissions scenarios that were used in that assessment. (see Appendix.) The study also used the same Variable Infiltration Capacity model that DWR used for downscaling, with Bias-Corrected Spatial Disaggregation.

The main difference between the non-stationary study and modeling by the Department of Water Resources, is that the non-stationary study did not correct model outputs to the historical hydrology. Instead, researchers ran the models without climate forcing, and compared the results to the historical hydrology. The graph below shows the cumulative probability of the different models compared with the observed 1951-2000 hydrology.



ANOVA and t-tests using a 95 percent confidence level found that results were not significantly different from historic hydrology. The graph and the statistical tests show that the models do a good job of capturing historic hydrology. This was one of the criteria for model selection.[27]

The results of the models under the A2 and B1 scenarios show a marked shift in climate. Most of the models show major increases in dry and critically dry years, and decreases in wet and below-normal years. The histograms on the next page shows the changes in the frequency of water year types for the Sacramento Valley Index.

All of the models show a significant increase in dry and critically dry years by the latter half of the century, with a corresponding decrease in wet and above normal years. Many of the models also show an increase in dry and critically dry years in the first half.

The table below shows water year types, averaged over all six GCM models, for the two scenarios.

[27] Climate Change Scenarios And Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, A Paper From the California Climate Change Center. Cayan et. al. op. cit.

Table 6. Percentage of Years in Each Water Type by Modeled Time Period and Emissions Scenario (italicized values are percent change from historical period)

	SVI					
	1951-2000 (%)		2001-2050 (%)		2051-2099 (%)	
	A2	B1	A2	B1	A2	B1
Critical	8.7	8.3	11.3 *(2.7)*	6.7 *(-1.7)*	18.4 *(9.7)*	14.0 *(5.6)*
Dry	7.7	10.0	12.0 *(4.3)*	15.7 *(5.7)*	19.4 *(11.7)*	20.1 *(10.1)*
Below Normal	23.3	21.3	23.3 *(0.0)*	17.3 *(-4.0)*	18.7 *(-4.6)*	19.4 *(-1.9)*
Above Normal	21.0	22.7	16.7 *(-4.3)*	20.7 *(-2.0)*	12.9 *(-8.1)*	18.4 *(-4.3)*
Wet	39.3	37.7	36.7 *(-2.7)*	39.7 *(2.0)*	30.6 *(-8.7)*	28.2 *(-9.4)*

The medium-high emissions scenario (A2) projections showed dry and critically dry years in the Sacramento Valley increasing to 23% of all years between 2000 and 2050, and to 38% of all years in the latter half of the century. Under this scenario, the incidence of dry and critically dry years would more than double.

The projections also showed a decrease in wet years.

In the Sacramento Valley, the A2 projections showed wet and above normal years decreased to 53% of all years in 2000-2050, and to 41.5% of years by the latter half of the century.

The lower greenhouse gas emissions scenario (B1) showed similar but less dramatic shifts.

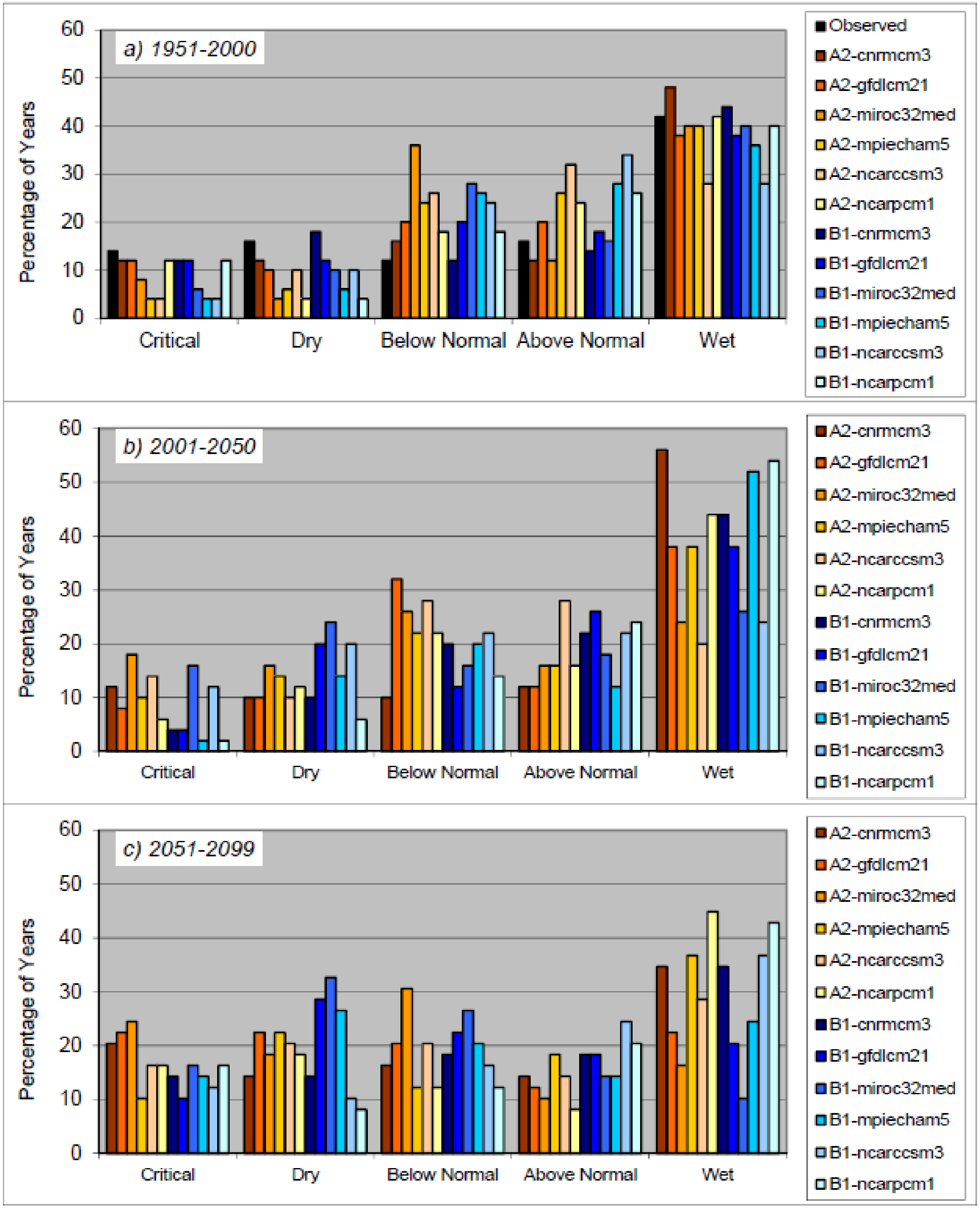
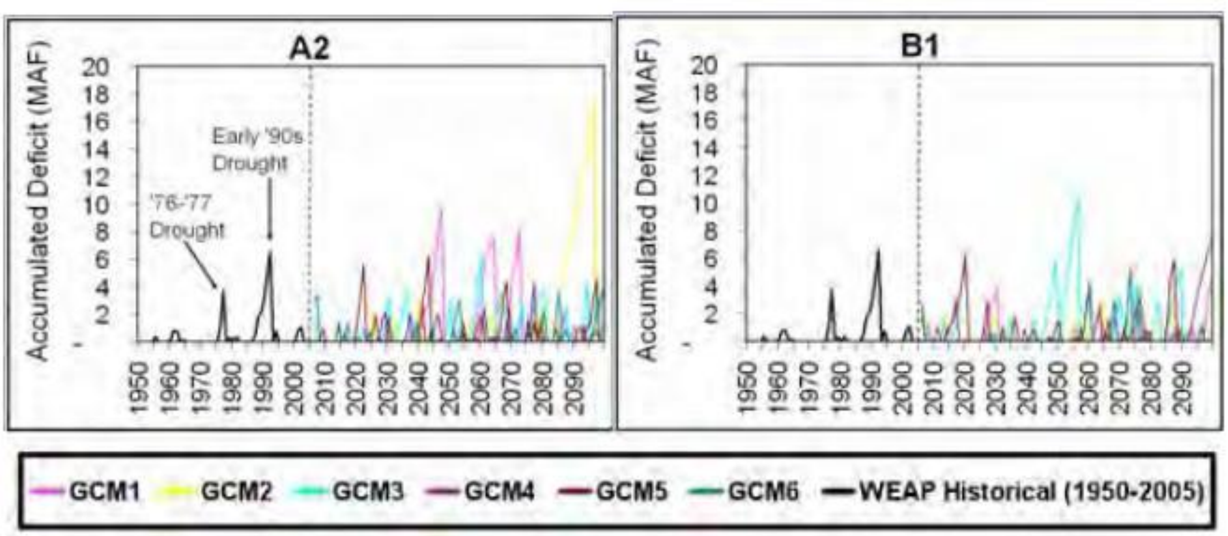


Figure 6. SVI Relative Frequency Histograms for (a) 1951-2000, (b) 2001-2050, and (c) 2051-2099

B. Climate Change Impacts on Water Supply and Agricultural Water Management In California's Western San Joaquin Valley, and Potential Adaptation Strategies, August 2009.[28]

This study, done by Brian Joyce, Vishal Mehta and David Purkey from the U.S. Center for the Stockholm Environmental Institute, Larry Dale from Lawrence Berkeley National Lab, and Michael Hanemann from the California Climate Center was released as part of the second California Climate Change Assessment in 2009, and used the same set of twelve global climate models / climate change scenarios. The study used a application of the Water Evaluation and Planning (WEAP) system developed for the Sacramento River basin and Sacramento Delta. WEAP is an integrated rainfall / runoff and water resources modeling framework that was developed in Stockholm, and has been used for water resources planning around the world. WEAP has also been used in climate modeling for the 2009 California Water Plan, and is being used in preparing the 2013 California Water Plan.

WEAP has the advantage that it does not rely on perturbation of historical precipitation or runoff patterns for projections. This allows the model to capture major shifts in historical patterns. The study found marked increases in the frequency of droughts, and under the A2 scenario, a mega-drought towards the end of the century. The graph below shows the results for different models.



In sum, two recent studies using two different methods of downscaling showed major changes in the structure of droughts in California. Both indicated an increase in the frequency and severity of droughts. This information is highly relevant to California water resources planning, and should incorporated into future planning studies.

[28] Climate Change Impacts on Water Supplies and Agricultural Water Management in the Western San Joaquin Valley and Possible Adaptation Strategies, Brian A. Joyce, Vishal K. Mehta, David R. Purkey, Larry L. Dale, and Michael Hanemann. California Climate Change Center, August 2009. Available at http://www.energy.ca.gov/2009publications/CEC-500-2009-051/CEC-500-2009-051-F.PDF

4. Previous modeling by DWR, which uses mapping onto the historic hydrology, should be re-evaluated with respect to risks of increased frequency and severity of droughts. This includes modelling of future streamflows and reservoir inflows used in the 2009 Climate Adaptation Strategy Assessment, and the 2009 and 2011 State Water Project Reliability Report.

For the 2006 California Climate Change Assessment,, the Department of Water Resources assessed the potential impacts of climate change on deliveries of the State Water Project and Central Valley Project. The modellers downscaled the global climate models using Bias Corrected Spatial Disaggregation, and then from the assessment as input to the Variable Infiltration Capacity model to generate regional estimates for runoff, snowpack, and soil moisture content. However, instead of using the predicted runoff information directly, the monthly stream flows were compared for a 30 year period with historic monthly stream flows to obtain a ratio. The monthly ratios were then mapped onto the historic record, multiplying each water year by the percentage increase or decrease.[29]

The problem with mapping the VIC model outputs back onto the 82 year historic record, is that it loses information from the global climate models that would change the frequency and severity of droughts, as well underestimating changes in annual and seasonal runoff. This can seriously underestimate impacts of climate change on both river flows and water supply.

The 2009 assessment of climate change impacts to the State Water Project and Central Valley Project attempted to solve some of the problems with the 2006 assessment by adjusting the predictions to correct annual and seasonal runoff to the mean values projected by the global climate models. However, this mapping still lost information about the structure of drought persistence.[30]

The Climate Change Modelling group noted these deficiencies in the final report, Using Future Climate Projections to Support Water Resources Decision Making in California.[31]

In Section 4.4 on "Future Climate Variability," the authors stated:

> In water resources planning, it is often assumed that future hydrologic variability will be similar to historical variability, which is an assumption of a statistically stationary hydrology. This assumption no longer holds true under climate change where the hydrological variability is non-stationary. Recent scientific research indicates that future hydrologic patterns are likely to be significantly different from historical patterns, which is also described as an assumption of a statistically non-stationary hydrology. In an article in *Science*, Milly et al. (2008) stated that "Stationarity is dead" and that "finding a suitable successor is crucial for human adaptation to changing climate."

The authors also noted that

> Some of the climate change impacts analyses currently conducted at DWR implicitly assume statistically stationary hydrology, such as the streamflow estimation method presented in Section 4.2.

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[29] Progress on Incorporating Climate Change into Management of California's Water Resources. Department of Water Resources, 2006. Available at http://www.water.ca.gov/climatechange/docs/DWRClimateChangeJuly06.pdf

[30] Using Future Climate Projections to Support Water Resources Decision Making in California, Francis Chung et. al., California Climate Center, Final Report, May 2009. Available at http://www.water.ca.gov/pubs/climate/using_future_climate_projections_to_support_water_resources_decision_making_in_california/usingfutureclimateprojtosuppwater_jun09_web.pdf

[31] Ibid.

The impacts analyses that used this streamflow estimation method and implicitly assumed statistically stationary hydrology included the 2009 impacts analysis of climate change on the State Water Project and Central Valley Project,[32] and the 2009 State Water Project Reliability Report.[33] It also appears that the same method was used in the 2011 State Water Project Reliability Report, without change.[34]

Since all of the Integrated Regional Water Management Plans that use State Water Project water used the SWP Reliability report in their planning analysis, the net effect of using this streamflow estimation is that all of these water agencies are implicitly assuming statistically stationary hydrology in their water planning. This could create systemic risk if the projections in the studies previous section are correct.

In addition, the 2009 State Water Project Reliability Report used a linear interpolation of global climate model outputs from 2050 with unforced data from the current period to estimate changes for 2029.[35] This essentially assumse that any 2029 reductions in inflows would half that of 2050 inflows. But comparing this assumption with the predictions for changes in precipitation in the 2009 Climate Scenarios assessment gives a much different picture. For most models, the changes at the Sacramento point in the 2005-2034 period are quite a bit more than half that of the 2035-2069. This could mean that there is a overestimation of potential deliveries in the near term. The same issue may also be present in the 2011 Delivery Reliability Report.

The Bay-Delta Conservation Plan modelers have modified the reservoir inflow estimation method to also include estimates of the changes to the probability distribution of global climate model predicted streamflows, including changes in the skew and standard deviation. This will include some information about the increased variability from heavier winter precipitation as well as drier months[36]. However, the monthly mapping technique still loses information about the structure of drought persistence, because it essentially assumes that it is a roll of the dice as to whether a dry month is followed by another dry month.

As discussed in previous sections, Global Climate Models contain information about persistence in increases sea surface temperatures, which can affect the ENSO and other circulation patterns, and influence the structure and persistence of droughts. Mapping output from global climate models onto the historic record of water years will inevitably lose much of this information.

In sum, while the techniques used by DWR to map output from global climate models to the historic record have improved, there are fundamental limitations to this approach. Wherever possible, projections should be compared with other modelling that does not map onto the historic record.

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[32] Using Future Climate Projections to Support Water Resources Decision Making in California, op. cit.

[33] The State Water Project Delivery Reliability Report 2009, Department of Water Resources, August 2010. Available at http://baydeltaoffice.water.ca.gov/swpreliability/Reliability2010final101210.pdf

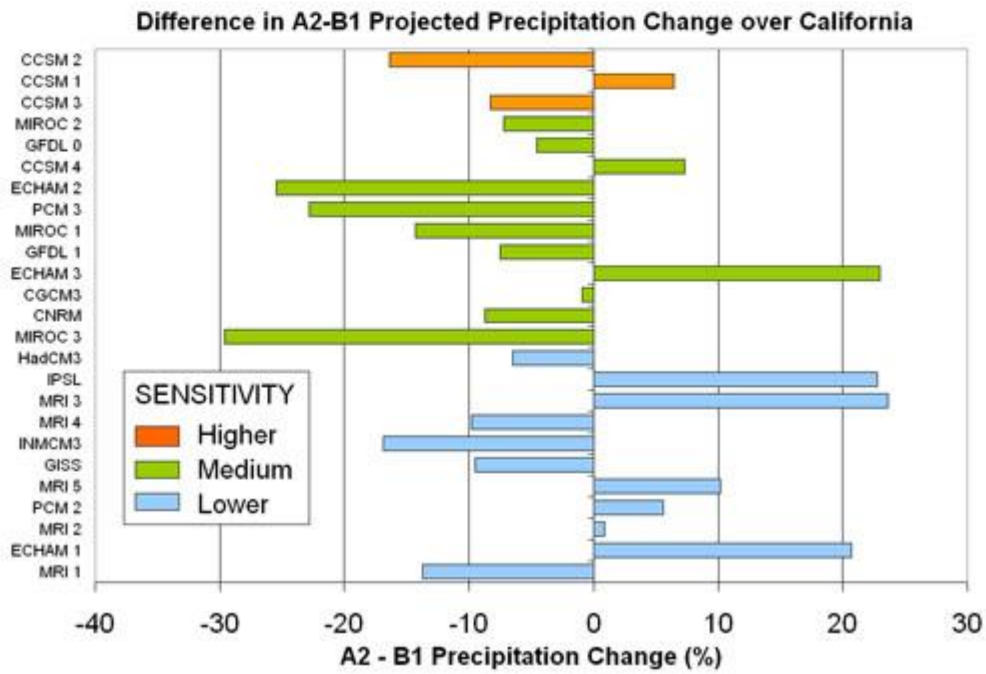
[34] Technical Addendum to The State Water Project Delivery Reliability Report 2011, Department of Water Resources, June 2012. Available at http://baydeltaoffice.water.ca.gov/swpreliability/2011DRR_FINAL_TechAddendum_062112.pdf

[35] SWP Delivery Reliability Report 2009, Ibid.

[36] Bay Delta Conservation Plan, Effects Analysis, Chapter 5, Section 5.2 Climate Change Approach and Implications for Aquatic Species. Available at http://baydeltaconservationplan.com/Libraries/Dynamic_Document_Library/BDCP_Effects_Analysis_-_Appendix_5_A_2_-_Climate_Change_Approach_and_Implications_for_Aquatic_Species_4-30-12.sflb.ashx

5. Model projections under higher greenhouse gas emissions scenarios tend to be drier. These scenarios are also more likely, given current trends. Whenever possible, information about higher GHG scenarios should be provided separately in planning studies, so that shifts under higher GHG scenarios can be assessed.

The graph below, from the California Climate Scenario Assessment team, shows the differences in projected precipitation change over California, between the B2 and A1 scenarios, for 25 models.[37] Sixteen of the 25 models (64%) show a decrease in precipitation with increased GHG emissions, and fifteen show a very significant decrease.

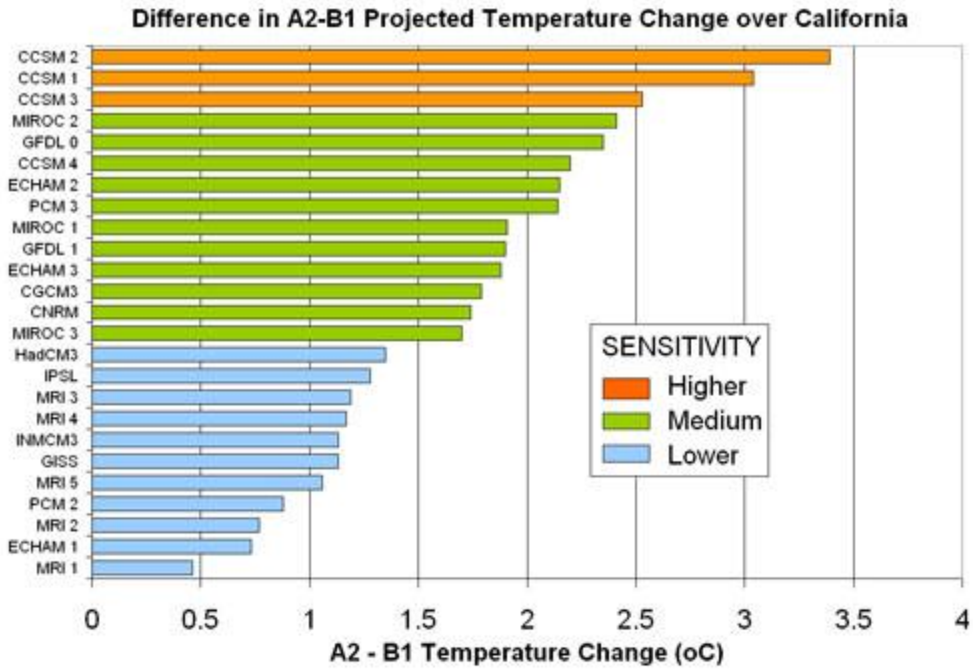


Source: California Climate Scenario Assessment team

.The graph above is color coded with regard to sensitivity of temperature change to higher GHG emissions. The graph below explains the color coding. The models were ranked on difference between projected temperatures between the A2 and B1 scenarios, and color coded. Blue was lowest sensitivity, green medium, and orange highest. The global climate models which show the highest temperature sensitivity with respect to changes in GHG emissions also tend to show large reductions in precipitation with higher GHG emission.

Of the highest sensitivity models, two thirds showed a marked decrease in precipitation between the A2 and B1 scenarios, and three fourths of the medium sensitivity models.

[37] California Climate Scenario Asssessment Team, Model Page. Available at http://meteora.ucsd.edu/cap/cccc_model_prelim.html#contents



For this reason, whenever possible, projections from the higher greenhouse gas emissions scenarios should be provided separately, so that the impacts can be assessed.

In addition, the higher GHG scenarios appear to be the most likely, given current trends in global development and increases in greenhouse gas emissions. In the discussion for the Cal-Adapt the draft Natural Resources Agency policy on Climate Adaptation states:

> "Of the two options provided by Cal-Adapt, the A2 scenario is the more realistic choice for decision-makers to use for climate adaptation planning. The B1 scenario is optimistic in the high level of international cooperation assumed. This cooperation would necessitate sweeping political and socioeconomic change on a global magnitude that is as yet unprecedented. The roughly two billion-person decline in population over the last half of the century is also reliant on broad assumptions of low mortality and low fertility. Generally, the B1 scenario might be most appropriately viewed as a version of a "best case" or "policy" scenario for emissions, while A2 is more of a status quo scenario incorporating incremental improvements."[38]

These same considerations should obviously be applied to statewide planning, including water resources planning.

[38] California Natural Resources Agency, draft California Climate Change Adaptation Policy Guide, April 2012. Available at http://resources.ca.gov/climate_adaptation/docs/APG_-_PUBLIC_DRAFT_4.9.12_small.pdf

6. The method of quantile mapping of climate change models, which has been used in BDCP modeling, implicitly assumes that wetter and drier futures are equally likely. This assumption should be re-examined in light of new knowledge about global climate models and the impacts of climate change on drought frequency and severity around the world. In addition, when quantile mapping is used, the projections of the wetter and drier ensembles should be provided separately so that the range of potential climate change impacts can be assessed.

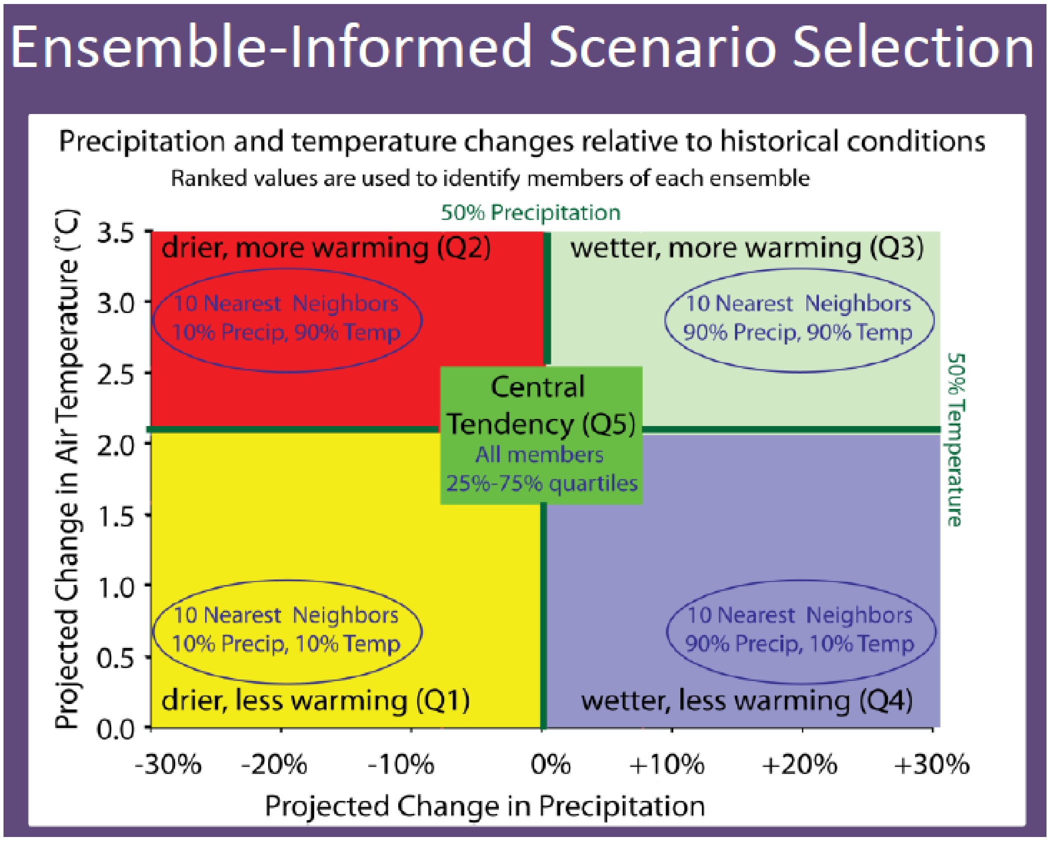
The method of quantile mapping of climate change models, used in the Bay Delta Conservation Plan assumes that wetter and drier futures in California are equally likely. This is substantially different than the median projections of 112 global climate models from the US Bureau of Reclamation Westwide Climate Risk Assessment, which were shown in the previous section. These ensemble median projection shows drying in Southern California and central Sierras by mid-century, and drying throughout California by 2070. It should also be noted that the quantile mapping method, while plausible, has not been tested and compared with the historic record in the same way that general ensemble models have.

This is a more detailed description of quantile mapping in BDCP. BDCP uses 112 climate change models, clustered under four different quartiles:

- Drier, less warming
- Drier, more warming
- Wetter, less warming
- Wetter, more warming

Each cluster of models is used to produce an ensemble model for each quartile. The ensemble models for each quartile are then combined into a fifth model, which captures the central tendency of all four of the individual models. The graph below, from a recent presentation by Jamie Anderson on selection of climate change scenarios, illustrates the ensemble scheme.[39]

[39] Jamie Anderson, presentation on Climate Change Approaches, Department of Water Resources, March 2012. Available at http://www.water.ca.gov/climatechange/docs/CCTAG_climate_change_approaches%20final_3-28-12_Jamie%20Anderson_with%20extra%20slides.pdf

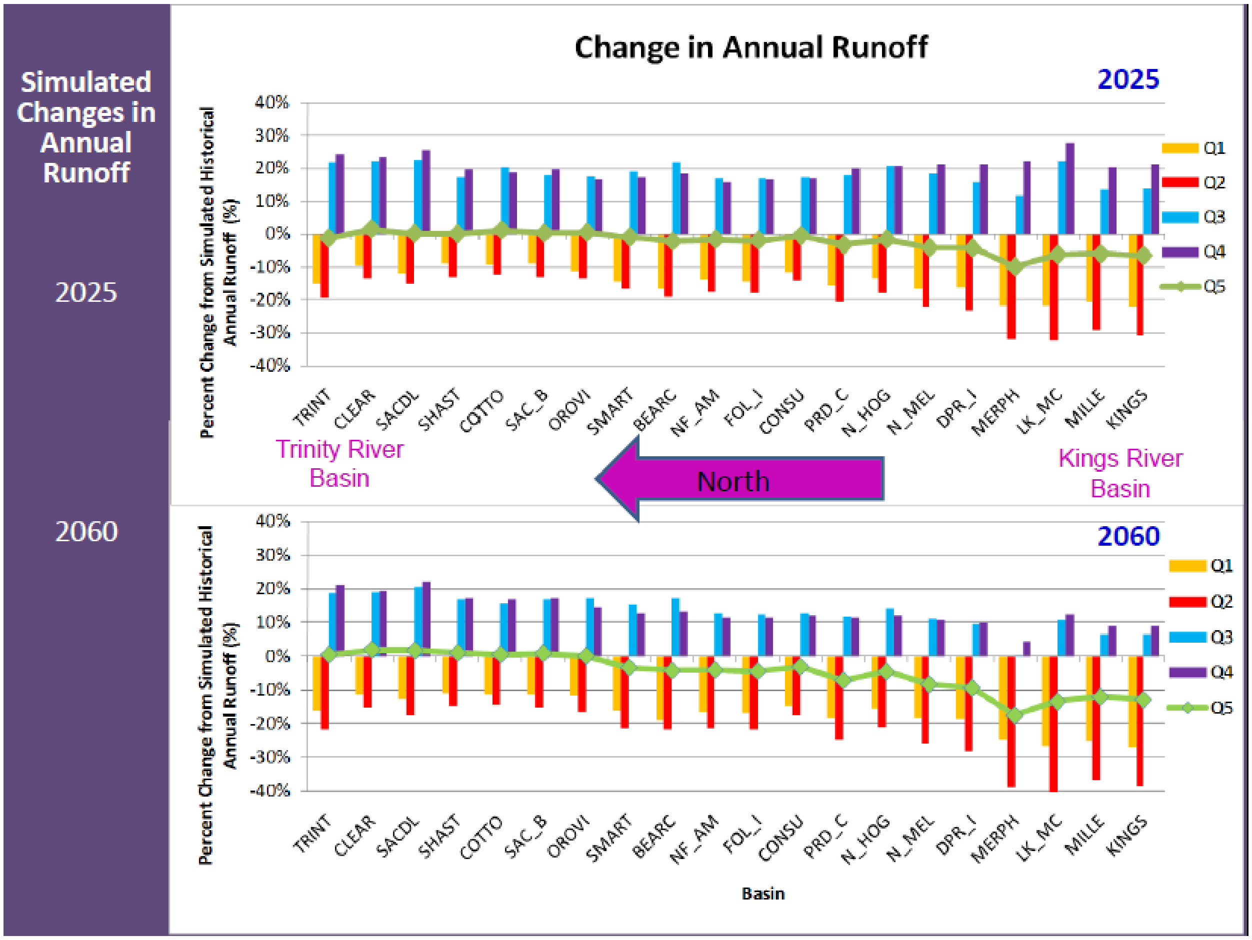


The central tendency model assumes not only that wetter and drier futures are equally likely, but that lower changes in temperatures due to global warming are as likely as higher changes. Given recent temperature trends across the globe, this assumption should be re-examined.

By its very structure, the quantile mapping process produces a central tendency prediction that is close to current norms of precipitation, since it assumes that wetter and drier futures are equally likely.

The graph below, also from Anderson, shows different trends in river runoff for the different quartiles. The drier, more warming Q2 model predictions include the worst case scenarios. The drier, less warming Q1 model predictions show weaker but still noticeable drying. The predictions of these models are red and yellow, and all show significant reductions in streamflows, more by the end of the century.

The Q3 wetter, more warming and Q4 wetter, less warming quartiles represents model which are less common in the space of all models. The graph below shows the different predictions of these wetter quartiles in light and dark blue. All the wetter models show increases in streamflow, but less by the end of the century, particularly in the San Joaquin Valley



The predictions of the final quartile, Q5, are shown in grey. Q5 is a combination of the four different wetter and drier quartile models, Q1 to Q4. This is the central tendency of the set of quartile models. As you can see, the central tendency model tends to reproduce the historical precipitation patterns in the near term. It is only over the long term, when the severe potential drying under the drier models far outweigh the effects of the wetter models, that the central tendency model begins to show some drying.

Using this ensemble model for BDCP could significantly underestimate effects of climate change in reducing precipitation and streamflow. For this reason, if the quartile mapping technique continues to be used, the predictions of the individual quartiles should also be provided.

7. Water planning and evaluation of future water project operations should consider not only total water deliveries, but risk taken in deliveries, particularly with respect to carryover storage.

One of the most notable conclusions in the 2006 climate change impacts assessment was that upstream storage was decreased, though not as seriously as in later simulations for the Bay Delta Conservation Plan. The graph below is an exceedance plot for end of year carryover storage.

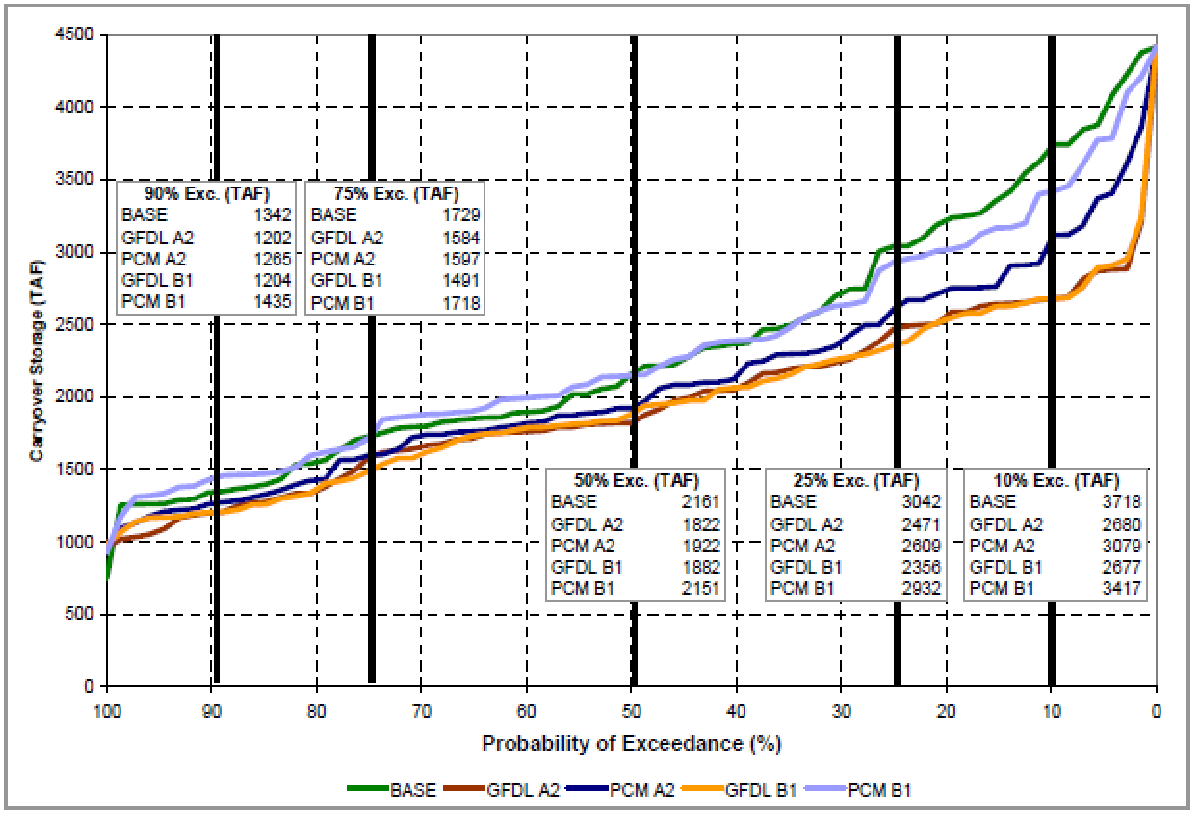


Figure 4.6 Exceedance Probability Plot of SWP Carryover Storage

The modelers noted, "Overall, with the drier climate scenarios, less water was delivered to Table A contractors and more risk with SWP carryover storage was taken to do it." Of particular concern were the number of months of dead storage in upstream reservoirs. These were months when basic demands for water supply for area of origin needs in the Sacramento Valley could not be met. The shortages would also greatly curtail exports.

Table 4.13 Months of Critical Shortages (Storage at Dead Pool)

	Shasta (months)	Oroville (months)	Folsom (months)
BASE	1	0	1
GFDL A2	31	0	28
PCM A2	29	0	22
GFDL B1	21	0	20
PCM B1	0	0	0

It is likely that actual impacts on end of year carryover storage would be much more severe, because of the limitations previously noted in the modeling. In addition, the modeling did not attempt to meet the3406b(2) requirements for Sacramento River flows to protect salmon. The modeling also only used the 2020 level of land development, and only sought to meet 2025 demands for water by Sacramento Valley water users.

The DWR modellers concluded:

> The length of shortages in GFDL A2, PCM A2, and GFDL B1 indicate that the delivery results presented for these scenarios in the next section are not always reliable. Too much risk was taken in the delivery allocation decisions of these three scenarios and not enough storage was carried into the drought periods as a result. In future climate change simulations, modifications to the rule that divides available water into delivery and carryover should be investigated as a means to prevent these shortages. Since CVP allocations are dependent on Shasta and Folsom storage, such modifications will likely alter the resulting delivery capability of the CVP as compared to the results presented in the next section.

It should be noted that maximizing water deliveries is not the same as increasing reliability. State Water Project and Central Valley Project allocation algorithms which attempt to minimize shortages and delivery interruptions could have much better performance in terms of drought deliveries. A 2000 Pier-funded simulation by Aris Georgakakos showed that an allocation algorithm which uses stochastic projections of runoff for nine months into the future to determine water deliveries could greatly improve water reliability, both in reducing shortages and meeting environmental targets.[40]

Georgakakos has done similar modeling of the Nile and Indus river valleys, the river systems in the world with the largest and second largest expanses of irrigated agriculture. The Central Valley is the third largest. Georgakakos' adaptive management system is currently being implemented on the Nile.

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[40] Reducing Vulnerability with Probabilistic Hydrological Forecasts and Modern Decision Support Systems, Aris Georgakakos. Presented at the Sixth Annual California Climate Change Research Symposium, 2009.

California Water Resources Exhibit List #2

Incorporating Drought Risk into California Water Planning

1. Climate Change Characterization and Analysis in California Water Resources Planning Studies, Final Report, Abdul Khan and Andrew Schwarz. Department of Water Resources December 2010, p. xvi. Available at http://www.water.ca.gov/climatechange/docs/DWR_CCCStudy_FinalReport_Dec23.pdf

2. Climate Change Scenarios And Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, A Paper From the California Climate Change Center. Dan Cayan, Mary Tyree, Mike Dettinger, Hugo Hidalgo, Tapash Das, Ed Maurer, Peter Bromirski, Nicholas Graham, and Reinhard Flick. Available at http://www.energy.ca.gov/2009publications/CEC-500-2009-014/CEC-500-2009-014-F.PDF

3. Temperature and precipitation trends in California: Global warming and Pacific Ocean influences. Steve LaDochy, Pedro Ramire1, Dan Killam, Ann Bui, William Patzert and Josh Willis. AMS Climate extended abstract.

4. West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections, U.S. Department of the Interior Bureau of Reclamation Technical Memorandum No. 86-68210-2011-01, March 2011.

5. Sarah Null and Josh Viers, Water and Energy Sector Vulnerability to Climate Warming in the Sierra Nevada: Water Year Classification in Non-Stationary Climates, California Climate Change Center, July 31, 2012

6. Climate Change Impacts on Water Supplies and Agricultural Water Management in the Western San Joaquin Valley and Possible Adaptation Strategies, Brian A. Joyce, Vishal K. Mehta, David R. Purkey, Larry L. Dale, and Michael Hanemann. California Climate Change Center, August 2009

7. The State Water Project Delivery Reliability Report 2009, Department of Water Resources, August 2010.

8. Technical Addendum to The State Water Project Delivery Reliability Report 2011, Department of Water Resources, June 2012.

9. Bay Delta Conservation Plan, Effects Analysis, Chapter 5, Section 5.2 Climate Change Approach and Implications for Aquatic Species.

10. California Natural Resources Agency, draft California Climate Change Adaptation Policy Guide, April 2012

11. Jamie Anderson, presentation on Climate Change Approaches, Department of Water Resources, March 2012.