Public Interest Energy Research (PIER) Program
White Paper

WATER AND ENERGY SECTOR VULNERABILITY TO CLIMATE WARMING IN THE SIERRA NEVADA:

Water Year Classification in Non-Stationary Climates

A White Paper from the California Energy Commission's California Climate Change Center

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Prepared by: University of California, Davis

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DISCLAIMER

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PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

This paper explores the sensitivity of water indexing methods to climate change scenarios to better understand how water management decisions and allocations will be affected by climate change. Many water management decisions, such as environmental flow requirements and water supply allocations, are based on numerical "water year type" designations. Water year type designations vary by region and index, but most are defined by some measure of runoff in the current water year compared to average historical runoff, with numerical thresholds categorizing year types. Climate change is anticipated to alter the timing and volume of runoff, and change the relative frequency of water year types as presently defined. California's Sacramento Valley and San Joaquin Valley Indices are used as a case study to examine climatic changes. These indices provide a framework for allocating and transferring water among users. Streamflow estimates for 1951–2099 from the climate-forced Variable Infiltration Capacity hydrologic model are used to estimate potential changes in runoff and water year type frequency, using six global circulation models for the A2 and B1 emissions scenarios. Results vary by emissions scenario and global circulation model, but indicate that critically dry water years in the Sacramento Valley and San Joaquin Valley are expected to be about 8 percent and 32 percent more likely by the latter half of the twenty-first century, respectively, if water year type definitions remain unchanged. If current water year type thresholds are maintained, more years will be classified as dry and less water will be allocated for environmental outflows, perhaps failing to provide adequate hydrologic variability to support species, habitats, and ecosystems. If thresholds are redefined to reflect the historical distribution of year types, the burden of climate change falls to consumptive users and water exporters. This case study illustrates how water policy and allocation frameworks were designed assuming climatic stationarity, and that adapting water policy (or maintaining the status quo) affects which users bear the burden of climate change.

Keywords: water year type, water management, climate change, water supply, environmental water

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Section 1: Introduction and Background

Water year classification systems and hydrologic indices are common for water planning and management because they simplify complex hydrology into a single, numerical metric that can be used in rule-based decision making. "Water years" avoid peak discharge during the start of a calendar year, typically beginning on October 1 in the northern hemisphere (Black 1996). Estimated unimpaired runoff for a water year is then further categorized by year type, such as wet, dry, or normal, compared to historical averages. Year type classification is tied to water resources planning, helping to answer the question of whether there is "enough" water (Redmond 2002), and allocations for various water uses are adjusted based on water year type (WYT). Water year type informs water allocation decisions for water supply, hydroelectric power generation, reservoir storage, and environmental protection (Simpson et al. 2004). Many drought and water year indices exist, including the Palmer Drought Severity Index (Palmer 1965), Standard Precipitation Index (McKee et al. 1993), Surface Water Supply Index (Shafer and Dezman 1982), Reclamation Drought Index (Weghorst 1996), and deciles (Gibbs and Maher 1967).

In California, the Sacramento Valley Index (SVI) and the San Joaquin Valley Index (SJI) are typically used to classify water years. They were designed with historical hydrology and are used in a complex and evolving water delivery allocation scheme shaped by operational constraints, regulatory restrictions, and objective demands (SWRCB 2000). Numerical thresholds separate each year type, set by winter and spring runoff volume for major rivers, as well as the previous year's index (a proxy for carryover storage). Generally, the SVI and SJI (or the sum of both indices known as the "Eight River Index") determine WYT for the State Water Project (SWP) and the federal Central Valley Project (CVP) to allocate water for out-of-stream users in the Bay Delta, environmental flows, and export limits to water users south of the Bay Delta (SWRCB 2000). Environmental flow objectives for the region include Bay Delta outflow, flow-dependent salinity and water temperature objectives, environmental flows for rivers in the Sacramento and San Joaquin watersheds, and salinity objectives in the San Joaquin River. The SVI and SJI directly influence water policy in the state through regulatory restrictions and directly affect dozens of federal, state, and local agencies (Simpson et al. 2004).

Global circulation models (GCMs) indicate that California's climate is expected to become warmer in the next century, although no clear trend exists for precipitation volume (Dettinger 2005; Cayan et al. 2008). The hydrology of coming decades will deviate from historical observations in terms of volume, magnitude, and timing (Milly et al. 2008). Results of climate-forced hydrological models indicate that climate change will shift snowfall to rainfall, resulting in earlier runoff with more winter runoff flooding and longer summer drought, and may further impair water quality (Null et al. 2010; Null et al. in review; Cayan et al. 2008; Barnett et al. 2008; VanRheenen et al. 2004). This may alter California's water allocation framework, which is determined by WYT compared to historical averages, and thus assumes climatic stationarity.

Previous research has indicated that the distribution of WYT is not stationary through time. Booth et al. (2006) showed the first and second half of a 100-year daily discharge dataset for California's Cosumnes River were significantly different. VanRheenen et al. (2004) and Vicuña (2006) noted that the distribution of WYTs shift with climate change. VanRheenen et al. (2004) modeled a shift in WYT thresholds to maintain the historical distribution for analyzing climate change impacts on the combined SWP/CVP system. Their work focused on human impacts and did not consider changes to flow objectives or whether their new thresholds provided enough water to sustain ecological integrity and function. Vicuña (2006) suggested changing the weights of seasons in the water year index to reflect changes in inflow timing. Other research has focused on improving understanding of the effects of El Niño-Southern Oscillation events or including the paleoclimate record to improve understanding of how runoff and WYT designations change through space and time (Anderson et al. 2001; Verdon-Kidd and Kiem 2010). There has been little research on climate change impacts to environmental flows, except for general agreement that competition could increase for minimum instream flow allocations (VanRheenen et al. 2004; Meyer et al. 1999), also increasing the economic costs of environmental requirements (Tanaka et al. 2006).

This paper evaluates the response of water year indices that were designed assuming climatic stationarity to climate change scenarios using a multiple model, multiple emissions scenario approach. It starts with a brief description of California's Sacramento and San Joaquin watersheds and Bay Delta. California's SVI and SJI are used as case studies with data from the climate-forced Variable Infiltration Capacity (VIC) model (Maurer et al. 2002; Liang et al. 1994). The SVI and SJI indices are fully described, as are climate projections from two commonly used emissions scenarios, the SRESA2 and SRESB1 and six GCMs from a relatively dry group of climate model results.[1] Limitations of water year indices and typing frameworks are briefly discussed. Results compare modeled historical 1951–2000 index means from the 12 runs (6 GCMs and 2 emissions scenarios) with observed data to test if the differences in mean flow are statistically significant between datasets. Next, simulated 1951–2000 runoff is compared with climate forced runoff projections for 2001–2050 and 2051–2099 to test for statistically significant change. Relative frequency histograms by WYT for the SVI and SJI demonstrate anticipated changes for California. Discussion focuses on alternative methods for adapting WYT indices to climate change, showing how methods affect water users differently. This paper highlights how water dedications, WYT classification, and climate are interrelated.

Study Area

California's west-slope Sierra Nevada rivers flow generally westward to their confluence with the Sacramento or San Joaquin Rivers, which merge and flow through the Bay Delta to the Pacific Ocean (Figure 1). The Sacramento and San Joaquin basins provide approximately 43 percent of California's total average annual surface runoff and are a source of drinking water for about two-thirds of the state's 35 million residents. Historical average annual flow is 18.2 million acre feet (maf) for the four northern SVI watersheds and 5.9 maf for the four southern SJI watersheds. However, California's hydrology is notably variable, and interannual variability is less predictable than seasonal or geographic variability. The driest year on record was 1977 with statewide annual runoff of 15 maf, while the wettest year was 1983 with annual runoff of 135 maf.

The CVP and SWP have pumps in the Sacramento-San Joaquin Bay Delta to divert water to southern California, portions of the Bay Area, and the western San Joaquin Valley. Following water development, environmental minimum flows are now mandated in some river reaches to

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[1] Models and climate scenarios were chosen to coincide with those used for the California Energy Commission's California Climate Change Research Center (www.climatechange.ca.gov/research/).

protect biological diversity, habitat complexity, and ecosystem services. In addition, the Bay Delta is an environmentally sensitive area, providing habitat for fish and wildlife (some species are protected under the state and federal Endangered Species Acts), and holding public trust value for common use (SWRCB 2000). Water year indices are used to establish operational rules by the State Water Resources Control Board (SWRCB) for regulating water quantity and quality through the Bay Delta (SWRCB 2000), by the Federal Energy Regulatory Commission (FERC) for hydropower relicensing (Viers 2011), and by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) for their Biological Opinions (USFWS 2008; NMFS 2009). Thus, WYT designations directly affect environmental flow dedications and water quality, as well as local diversions and water exports from the Bay Delta.

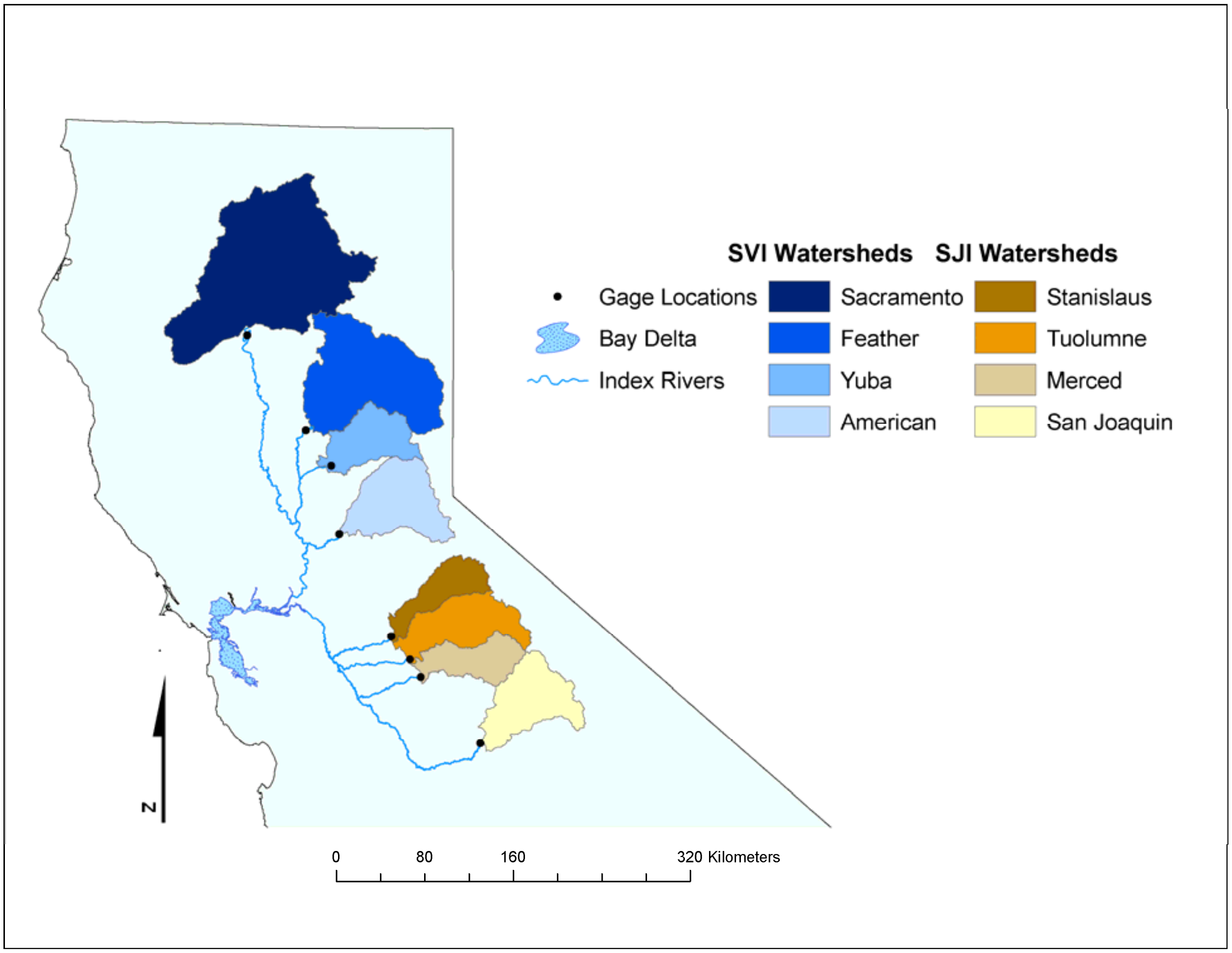

Figure 1. Sacramento and San Joaquin Watersheds with Gage Locations for Water Year Type Indexing

The SVI was developed by the SWRCB in 1989 (from a previously existing Sacramento River classification scheme), and the SJI was developed in 1991 (CDWR 1989, CDWR 1991). The general concept was to divide runoff into wet, near-normal (above normal and below normal), dry, and critical categories (weighted approximately 30 percent, 20 percent, 20 percent, 15 percent, and 15 percent), respectively, of the historic record to aid management of the water projects and provide an index of water supply for the public (CDWR 1989). Water shortages were expected during critical years (Roos, pers. comm. 2011). In practice, insufficient water is available for water export demands south of the Bay Delta pumps in critical, dry, and below-normal years for August, September, and October (SWRCB 2000). The SVI is the most important for managing the Bay Delta, although the SJI impacts environmental flow objectives and the "Eight River Index" uses both Sacramento and San Joaquin system runoff to determine salinity in Suisun Bay.

Sacramento Valley Index (SVI)

The SVI (also known as the "Four River Index" and the "40-30-30 Index") uses the sum of estimated unimpaired runoff from the following gages: Sacramento River above Bend Bridge, Feather River at Oroville, Yuba River near Smartsville, and American River below Folsom Lake (CDEC 2010) (Figure 1). It is calculated using Equation 1, and year type classification is based on the thresholds in Table 1. The term for the previous year's index is a proxy for the effect of carryover storage on system capability (CDWR 1989).

$$\text{SVI} = (0.4^{*}\text{current Apr–Jul runoff})+(0.3^{*}\text{current Oct–Mar runoff})+(0.3^{*}\text{previous year's index})^{2} \quad \textbf{(1)}$$

Table 1. Sacramento Valley Index and San Joaquin Valley Index Year Type Classification Thresholds

Water Year Type	Sacramento Valley Index (maf)	San Joaquin Valley Index (maf)
Wet	≥9.2	≥3.8
Above Normal	>7.8 and <9.2	>3.1 and <3.8
Below Normal	>6.5 and ≤7.8	>2.5 and ≤3.1
Dry	>5.4 and ≤6.5	>2.1 and ≤2.5
Critical	≤5.4	≤2.1

San Joaquin Valley Index (SJI)

The SVI and SJI were intentionally given different weights on each segment of the index to account for snowmelt-dominated runoff and occasional large winter floods that provide less water deliveries in the San Joaquin basin (CDWR 1991). The SJI (or the "60-20-20 Index") uses the sum of unimpaired runoff from Stanislaus River below Goodwin Dam, Tuolumne River below La Grange Dam, Merced River below Merced Falls, and San Joaquin River inflow to Millerton Lake (CDEC 2010) (Figure 1). It is calculated using Equation 2, and year type thresholds are based on the values in Table 1.

$$\text{SJI} = (0.6^{*}\text{current Apr–Jul runoff})+(0.2^{*}\text{current Oct–Mar runoff})+(0.2^{*}\text{previous year's index})^{3} \quad \textbf{(2)}$$

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[2] Maximum of 10.0 maf for previous year's index term to account for required flood control reservoir releases.

Historical Water Year Thresholds

For planning purposes, year types are set by forecasts beginning in February (and updated monthly through May), although for this study we use estimated actual unimpaired runoff (CDEC 2010) or modeled data. Values of the SVI and SJI account for geographic variation in streamflow, so the SVI has greater thresholds than the SJI (Table 1). The historical relative frequency of year types also varies slightly between the SVI and SJI. For example, the threshold for critically dry year types falls at the 13th percentile of the observed period of record for Sacramento Valley streamflow, but at the 17th percentile for San Joaquin Valley streamflow. Operationally, this means there is a slightly higher chance that any year will be critically dry in the San Joaquin Valley, and more environmental flow is allocated from Sacramento Valley rivers than the San Joaquin rivers. The opposite is true for dry and below-normal year types.

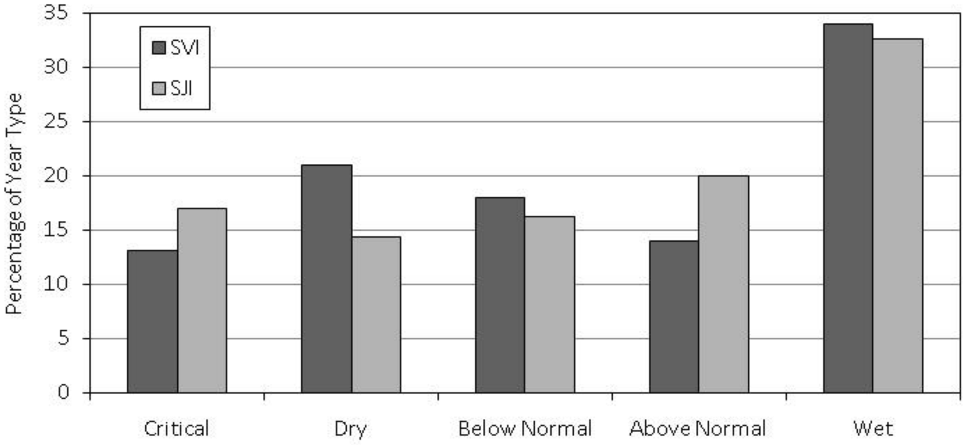

Figure 2. Current Water Year Type Variability Using Observed Historical Data (1905–2000)

Section 2: Methods

Modeled Hydrologic Data

A water year index framework was used to assess hydrologic response from the Sacramento and San Joaquin basins with climate change. Downscaled, climate-forced streamflow estimates were from the VIC model, a large-scale, distributed, physically based hydrologic model that balances surface energy and water over a grid (Liang et al. 1994; Maurer et al. 2002). VIC uses sub-grid representation for vegetation, soils, and topography to retain local variability for partitioning precipitation into runoff and infiltration, and uses non-linear representation for simulating baseflow. Data were downscaled using bias correction and spatial downscaling (BCSD), a statistical downscaling method that preserves monthly climate patterns between coarse and fine resolutions (Maurer and Hidalgo 2008). Water routing was post-processed to estimate streamflow at river outlets (using an algorithm developed by Lohmann et al. [1996] as

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[3] Maximum of 4.5 maf for previous year's index term to account for required flood control reservoir releases.

cited in Cayan et al. 2008). Parameterization for deriving streamflow is identical to that used by VanRheenen et al. (2004) for the Sacramento–San Joaquin basin. VIC has previously been used to assess the hydrologic effects of climate change in the western United States (Cayan et al. 2008; VanRheenen et al. 2004; Maurer et al. 2002; Vicuña et al. 2007; and others).

This application of VIC used a 1/8° spatial grid and a daily timestep (later aggregated to a monthly timestep) for the 1951–2099 water years. Twelve VIC runs were analyzed, with climate input data from six GCMs for the A2 and B1 emissions scenarios (Table 2). Modeled water years were separated into three time periods: 1951–2000 constitutes the historical time period, and simulations of future years were split into two groups, 2001–2050 and 2051–2099 for near- and far-term estimates of runoff conditions. Water years (Oct–Sep) are used throughout this paper.

Table 2. Climate Scenarios, GCMs, and Modeled Time Periods

Climate Scenarios	Global Circulation Models	Time Periods
SRESA2	CNRM CM3	Historical (1951–2000)
SRESB1	GFDL CM2.1	Near-term (2001–2050)
	CCSR MIROC 3.2 medium resolution	Long-term (2051–2099)
	MPI-OM ECHAM5	
	NCAR CCSM3.0	
	NCAR PCM1	

Differences between emissions scenarios are due to uncertainty in human actions such as population growth and greenhouse gas (GHG) emissions, while differences in GCMs are due to uncertainty in climate models such as representation of physical processes and sensitivity to GHG forcings. The A2 scenario has more severe climate change, assuming maximum carbon dioxide (CO_2) emissions of 850 parts per million (ppm), continuously increasing global population, and slow economic growth. The B1 scenario is more moderate, assuming maximum carbon dioxide (CO_2) emissions of 550 ppm, global population that peaks mid-century and later declines, and global sustainability solutions that introduce resource-efficient technology (IPCC 2000).

Statistical Analysis

One-way ANOVA and Student's t-tests were used to analyze whether differences in mean runoff between modeled and observed data or between time periods are statistically significant. First, the means of the modeled historical 1951–2000 datasets (modeled A2 and B1 simulations) were tested against observed historical data for the same time period. (The six GCMs for each A2 or B1 emissions scenarios are grouped to reduce uncertainty associated with individual climate models.) The same tests were used to determine whether changes in the means of the SVI and SJI indices through time are statistically significant (simulated 1951–2000, 2001–2050, and 2051–2099). ANOVA was used to test the means of all three A2 and B1 time periods, reducing the risk of a type I error (which would show a difference in means when, in reality, none exists). Student's t-tests were used to assess whether the means of two groups are statistically different, so each time period can be compared to see when most change occurs. Mean cumulative frequency distributions for each emissions scenario illustrated how year type indices shift to represent drier conditions. All statistical analyses were completed using SAS's JMP v8.0.2 statistical software.

Limitations

Water year and drought indices are routinely used to assess meteorological, agricultural, hydrological, and socioeconomic drought. They are helpful for categorizing water years into similar types, allowing water managers and policymakers to quantify years, visualize variability, and guide water operations. However, they have inherent limitations. Water year indices can be used by policymakers who have poor understanding of the flaws and driving factors of the indices. Further, classifications of WYTs are typically arbitrary, with little scientific rigor (Goodrich and Ellis 2006). Quiring (2009) developed methods for objectively determining index thresholds and operational drought definitions, but discovered that few, if any, entities use objective methods for deciding on thresholds. By examining the magnitude and duration of flood pulse events, Booth et al. (2006) found that more inter-annual variability exists than is captured in WYT classifications. Water year indices focus on runoff volume, with less emphasis on timing (Vicuña 2006). Thus, they are poorly suited to evaluate intra-annual or seasonal shifts in runoff from climate change. Finally, more research is needed to accurately describe the ecological differences between year types, as well as determine how much water ecosystems need.

Section 3: Results

Water Year Index Means

For the SVI and SJI historical 1951–2000 datasets (comparing observed, modeled A2, and modeled B1), there is no significant difference between water year runoff means, October to March runoff means, or April to July runoff means using a 95 percent confidence level (Table 3).

Table 3. ANOVA and t-Test Significance for Historical Time Period, 1951–2000 (values < 0.05 are statistically significant at the 95 percent confidence level)

		ANOVA Significance (pr>F)	**Student's t-Test Significance (p-value)**	
Watershed		All GCMs (Observed, A2, & B1)	Observed vs. A2	Observed vs. B1
Sacramento	SVI	0.65	0.36	0.41
	Oct–Mar Runoff	0.97	0.82	0.85
	Apr–Jul Runoff	0.38	0.17	0.19
San Joaquin	SJI	0.62	0.35	0.34
	Oct–Mar Runoff	0.47	0.23	0.25
	Apr–Jul Runoff	0.46	0.23	0.23

This indicates that the modeled hydrological data are representative of historical water year index values. Figure 3 shows the cumulative frequency distributions for observed and modeled SVI and SJI in the 1951–2000 historical period. The A2 family is shown with warm colors and the B1 with cool colors. For SVI, GCMs tend to over-predict index values in dry years when the historical index is less than approximately 8 maf (which includes the critical, dry, and below-normal year types). For SJI, GCMs typically slightly under-predict index values for all year types.

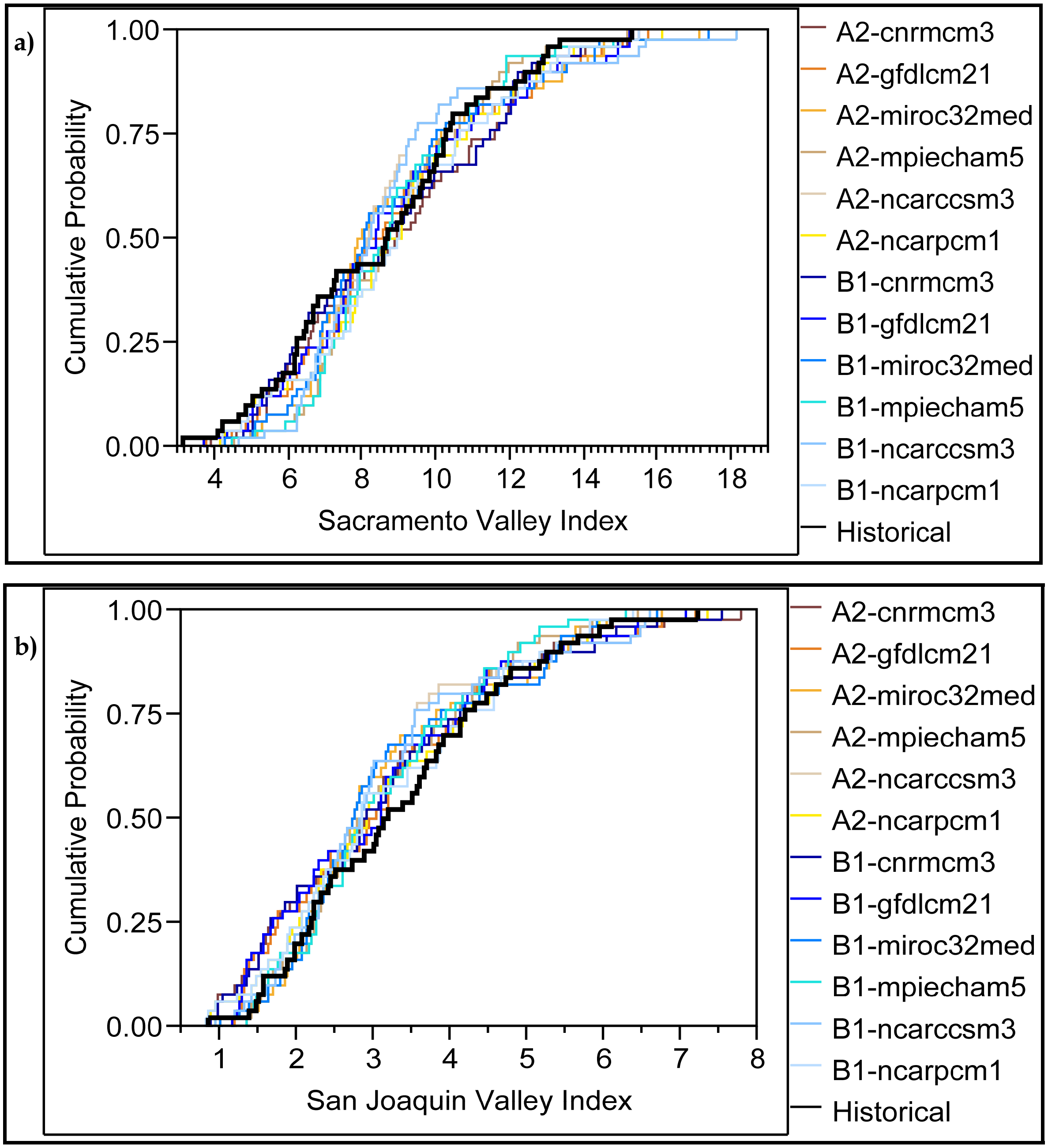

Figure 3. Cumulative Frequency Distributions for Observed vs. Modeled 1951–2000 Historical Time Period for (a) SVI and (b) SJI (note x-axis scale change between figures)

ANOVA and t-tests were again used to determine whether modeled mean SVI, SJI, October–March runoff, and April–July runoff are statistically different between modeled time periods (simulated 1951–2000, 2001–2050, 2051–2099, as shown in Table 4). ANOVA results indicate that SVI and SJI index means are statistically different between all time periods, as are April–July runoff means using a 95 percent confidence level (simulated average annual flow data are given in Table 5). When index means are compared between time periods using t-tests, SVI and SJI means are always statistically different between the first and third time period, and between the second and third time periods. However, only the means of the SJI A2 emissions scenario are significantly different between the first and second time period. This implies that for most simulations, changes in mean water year index values are most detectable in the latter half of the twenty-first century.

Table 4. ANOVA and t-Test Significance for the Modeled 1951–2000, 2001–2050, and 2051–2099 Time Periods. Black values indicate statistically different means ($p < 0.05$) between time periods.

			ANOVA Significance (pr>F)	**Student's t-test Significance (p-value)**		
	Index and Data	ES	All time periods	1951-2000 vs. 2001–2050	2001–2050 vs. 2051–2099	1951–2000 vs. 2051–2099
Sacramento	SVI	A2	0.0002	0.12	0.0109	< 0.0001
		B1	< 0.0001	0.84	< 0.0001	0.0001
	Oct-Mar Runoff	A2	0.34	0.47	0.45	0.14
		B1	0.10	0.04	0.13	0.61
	Apr-Jul Runoff	A2	< 0.0001	< 0.0001	< 0.0001	< 0.0001
		B1	< 0.0001	0.0013	< 0.0001	< 0.0001
San Joaquin	SJI	A2	< 0.0001	0.0010	< 0.0001	< 0.0001
		B1	< 0.0001	0.13	< 0.0001	< 0.0001
	Oct-Mar Runoff	A2	0.15	0.43	0.25	0.05
		B1	0.18	0.09	0.15	0.79
	Apr-Jul Runoff	A2	< 0.0001	0.0002	< 0.0001	< 0.0001
		B1	< 0.0001	0.0104	< 0.0001	< 0.0001

Table 5. Modeled average annual flow by time period (maf is millions of acre-feet)

			Average Annual Flow (maf)		
	Index and Data	ES	1951-2000	2001-2050	2051-2099
Sacramento	Annual Runoff	A2	20.09	19.38	18.29
		B1	20.02	20.29	18.23
	Oct-Mar Runoff	A2	11.70	12.08	12.50
		B1	11.66	12.68	11.92
	Apr-Jul Runoff	A2	7.34	6.31	4.91
		B1	7.31	6.60	5.39
San Joaquin	Annual Runoff	A2	6.03	5.50	4.79
		B1	6.02	5.81	4.83
	Oct-Mar Runoff	A2	2.24	2.35	2.50
		B1	2.24	2.45	2.27
	Apr-Jul Runoff	A2	3.48	2.91	2.08
		B1	3.48	3.09	2.33

Mean April–July runoff is statistically different between all time periods. Runoff volume change for April–July is given 40 percent and 60 percent weight for the SVI and SJI, respectively. Changes to this runoff season are likely driving mean index values. These findings underscore existing research demonstrating expected climate-induced changes to runoff timing (Cayan et al. 2008; Null et al. 2010; VanRheenen et al. 2004; Knowles and Cayan 2002). Cumulative frequency distributions show modeled shifts in index values by time period with vertical bars delineating current WYT thresholds for SVI (Figure 4) and SJI (Figure 5).

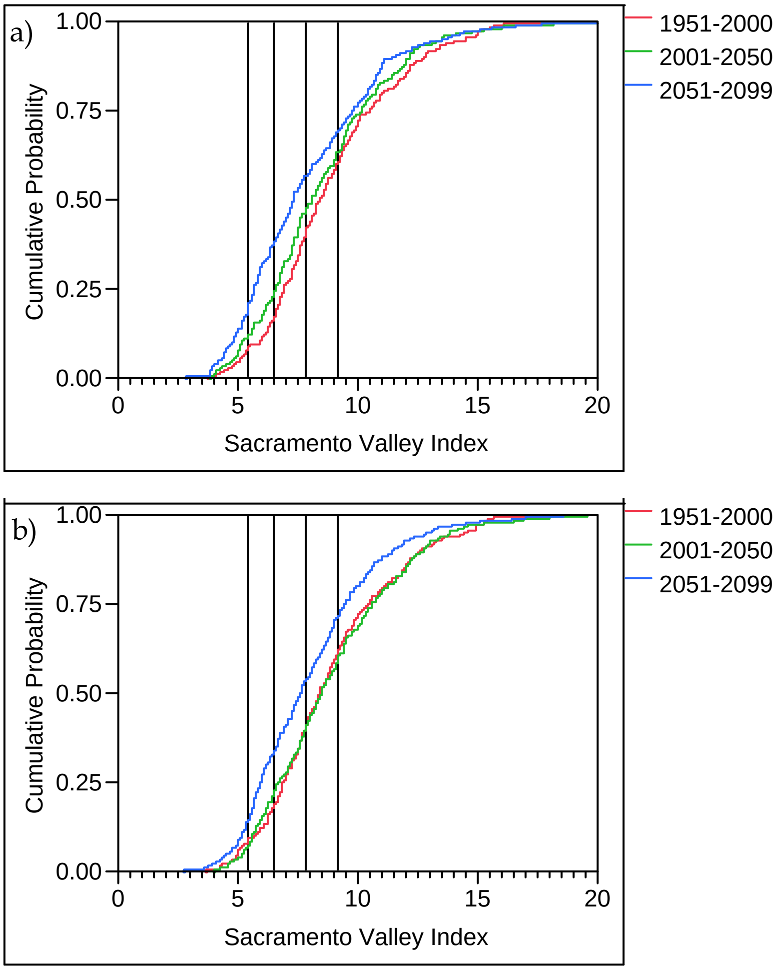

Figure 4. SVI Cumulative Frequency Distributions by Time Period for (a) A2 and (b) B1 (vertical bars show current WYT thresholds)

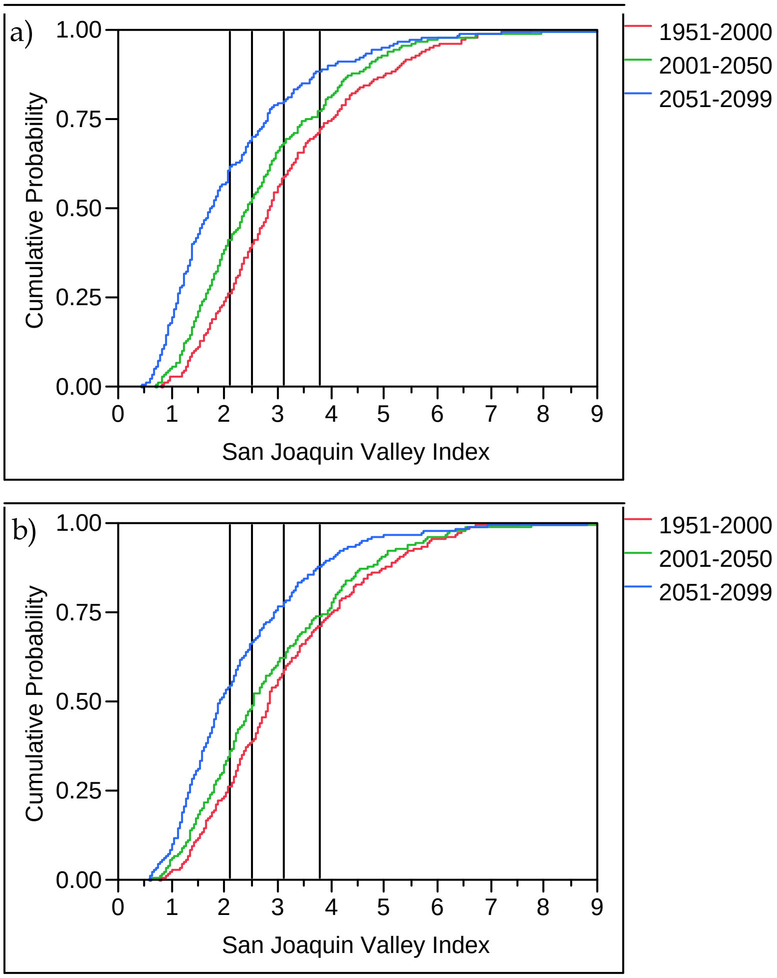

Figure 5. SJI Cumulative Frequency Distributions by Time Period for (a) A2 and (b) B1 (vertical bars show current WYT thresholds)

Water Year Types

If the hydroclimate changes in coming decades, then the relative frequency of WYTs will change, as will water allocations which are based on WYTs. The relative frequency that water years are classified as each year type is illustrated with histograms by modeled time period for SVI (Figure 6) and SJI (Figure 7) (note scale change between figures). Observed data are included for the 1951–2000 historical period (Figure 6a and Figure 7a) for visual corroboration of modeled and observed data. Differences between emissions scenarios (warm hues versus cool hues) are due to uncertainty in human actions such as population growth and GHG emissions, while differences in GCMs (variability within the warm hues or cool hues) are due to uncertainty in climate models, such as representation of physical processes and sensitivity to radiative forcings.

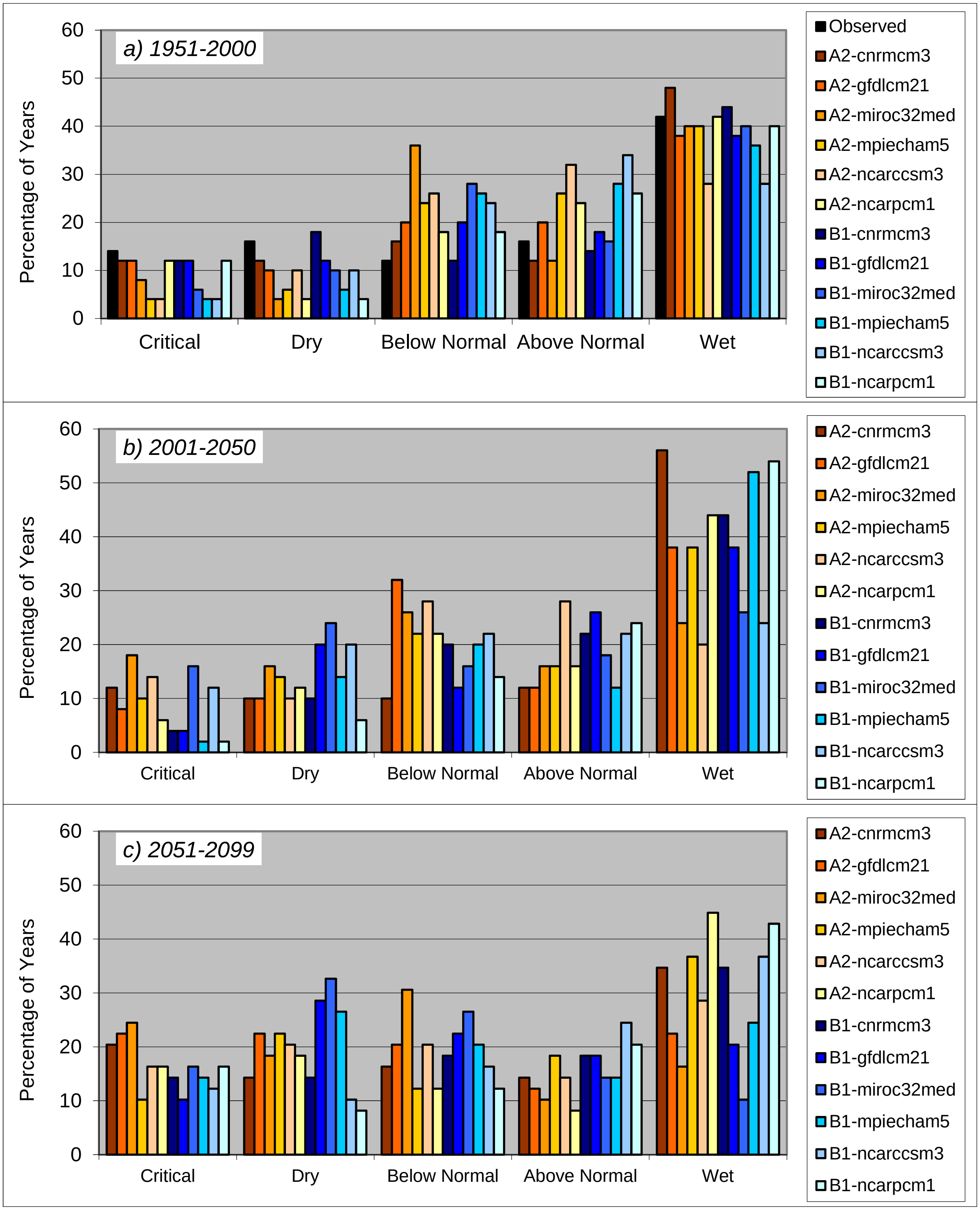

Figure 6. SVI Relative Frequency Histograms for (a) 1951–2000, (b) 2001–2050, and (c) 2051–2099

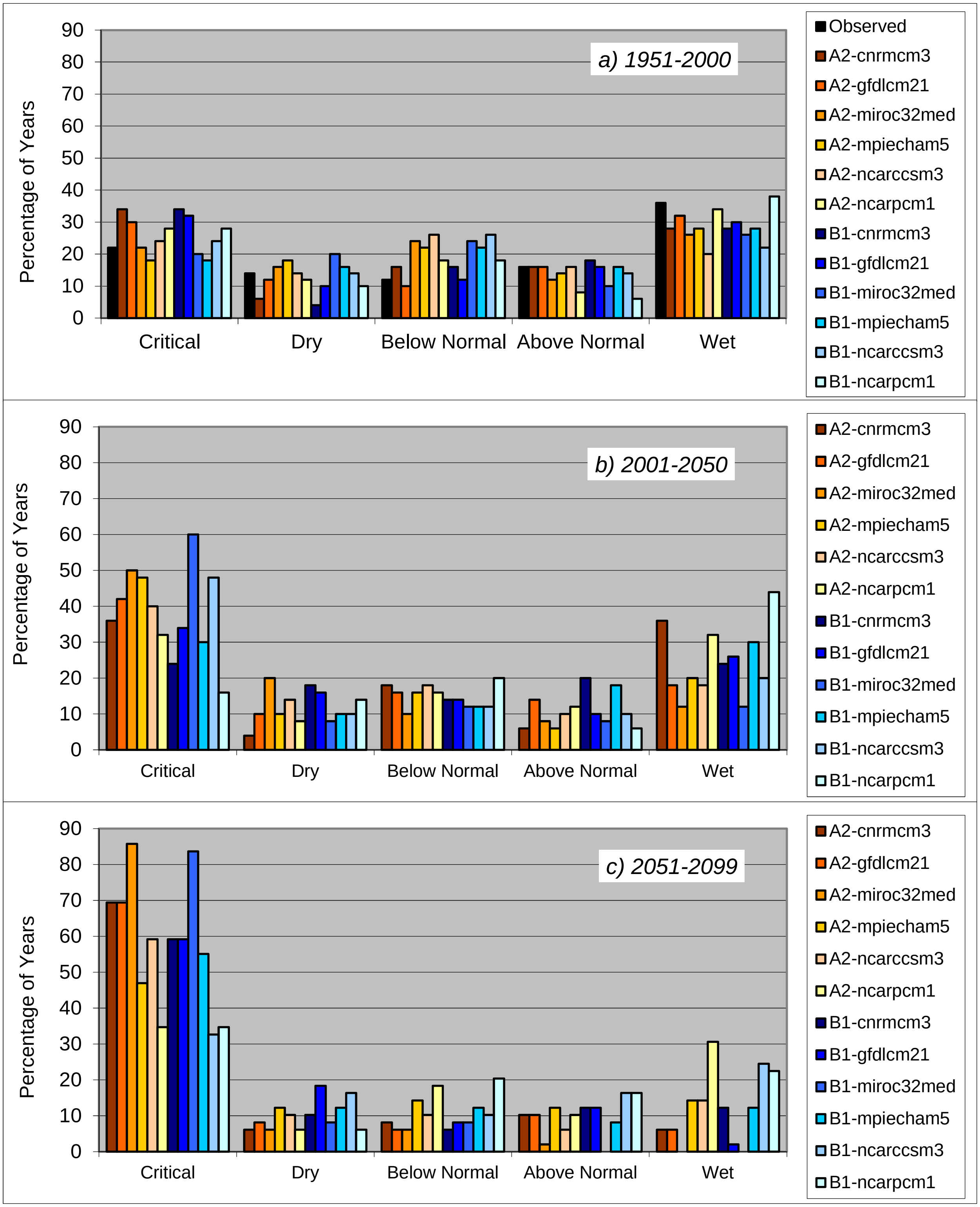

Figure 7. SJI Relative Frequency Histograms for (a) 1951–2000, (b) 2001–2050, and (c) 2051–2099

Results indicate the relative frequency of WYTs is expected to shift throughout the next century. For the SVI, modeling suggests a more even distribution of WYTs in each category by the end of the century (Figure 6). Projections from both the A2 and B1 emissions scenarios indicate the Sacramento Basin will likely have more dry and critical years, and fewer normal and wet years throughout the current century (Figure 6, Table 6). By the latter half of the twenty-first century (2051–2099), 6 to 10 percent more critical years and 10 to 12 percent more dry years could occur if water year thresholds remain the same. The more drastic changes could occur if the higher CO_2 emissions and increasing population assumptions of the A2 emissions scenarios are realized.

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)*
	SJI					
	1951-2000 (%)		2001-2050 (%)		2051-2099 (%)	
	A2	B1	A2	B1	A2	B1
Critical	26.0	26.0	41.3 *(15.3)*	35.3 *(9.3)*	60.9 *(34.9)*	54.1 *(28.1)*
Dry	13.0	12.3	11.0 *(-2.0)*	12.7 *(0.3)*	8.2 *(-4.8)*	11.9 *(-0.4)*
Below Normal	19.3	19.7	15.7 *(-3.7)*	14.0 *(-5.7)*	10.5 *(-8.8)*	10.9 *(-8.8)*
Above Normal	13.7	13.3	9.3 *(-4.3)*	12.0 *(-1.3)*	8.5 *(-5.2)*	10.9 *(-2.5)*
Wet	28.0	28.7	22.7 *(-5.3)*	26.0 *(-2.7)*	11.9 *(-16.1)*	12.2 *(-16.4)*

For the SJI, considerably more years fall into the critical category with fewer years in all other year types, particularly toward the end of this century (Figure 7). Results indicate a 28 to 35 percent increase in critical water years by the last half of this century, with the larger changes under A2 assumptions (Figure 7, Table 6). The distribution of water years could go through a major shift toward the second half of the century. Changes to the relative frequency of SJI year types could affect water users in the Sacramento watershed when the eight-river index is used (as is the case for determining Bay Delta export limits as a percentage of Delta inflow) (SWRCB 2000). These findings reiterate results from VanRheenen et al. (2004), who also observed more severe streamflow volume reduction in the San Joaquin Basin than the Sacramento Basin.

Section 4: Discussion

Threshold-based water year classification forms the framework for flow objectives in the Bay Delta and Sierra Nevada rivers, consumptive water uses in the Bay Delta, and licensure rules for hydropower generation in the Sierra Nevada, and shapes water deliveries for much of California's population. The SVI and SJI are numerical indices, so they can continue to be used with severe climatic change as they are. However, WYT classifications and threshold definitions will likely become less representative with climate change. By the end of this century the distribution of particular year types is anticipated to be significantly different from the historical record.

Previous work has indicated that average Bay Delta CVP/SWP exports are especially reduced during summer and fall from reduced snowpack, and that exports are most sensitive to climate change during very wet or very dry years (Anderson et al. 2008). This paper shows the frequency of very dry years is likely to increase significantly using data from a relatively dry group of climate models. More dry years may shift climate change–related impacts, altering the relative water use winners and losers, as well as shifting associated economic costs.

If current WYT thresholds are maintained, substantially more dry and critically dry years are anticipated to occur as explained in the results section above and further illustrated with the modeled distribution of WYT using historical thresholds (Figure 8; black bars show thresholds, and wider bars quantify uncertainty between the A2 and B1 runoff estimates). This would disproportionately impact environmental uses (for example, Bay Delta outflows are reduced by approximately 36 percent between wet and dry years), although deliveries to all water users would be reduced. With persistent dry conditions under this scenario, California risks failing to provide adequate baseflow and hydrologic variability to support various ecosystems, and failing to protect species and habitat as required by the state and federal Endangered Species Acts, the Natural Community Conservation Planning Act, and the Clean Water Act. Additional confounding regulatory drivers include, but are not limited to, regulatory oversight by the SWRCB to uphold public trust values and expanded water quality enforcement through the Porter-Cologne Water Quality Control Act (SWRCB 2011), hydropower relicensing through FERC (Viers 2011), or the emergence of state interest in safeguarding public trust values through Section 5937 of the California Department of Fish and Game code (Baiocchi 1980).

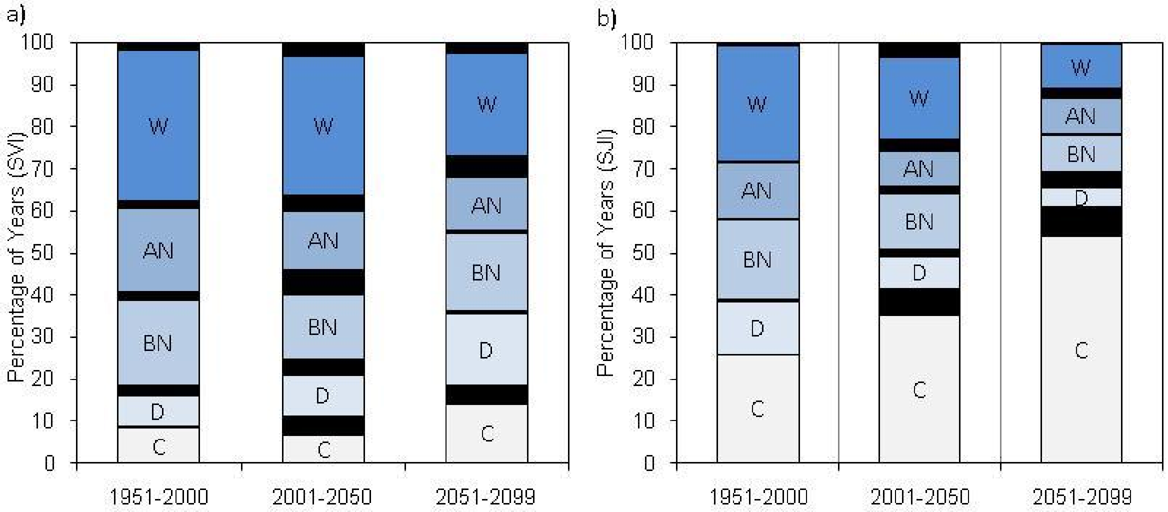

Figure 8. Modeled Distribution of Water Year Types Using Historical Thresholds Where Black Bands Show Uncertainty Between A2 and B1 Projections for (a) SVI and (b) SJI (Note scale change between figures. C is critically dry, D is dry, BN is below normal, AN is above normal, and W is wet.)

Conversely, WYT thresholds could be redefined to reflect changes in climate, recognizing that the normal years of the future may resemble the critical or dry years of the past century (Figure 9). The thresholds determining year types must be lowered to maintain the historical distribution of water years with climate-driven modeled data (CDWR 1989; CDWR 1991). For example, for modeled SJI 1951-2000 data, the threshold for critically dry year types should be set at about 1.7 maf for 17 percent of years to be in the critically dry year type, but the threshold would have to be reset between 0.9 to 1.1 maf for 17 percent of years to be in the critically dry category by 2051-2099. If volumetric environmental flow requirements tied to each WYT remain the same, much of the burden of climate change would fall on human water uses under this scenario and regulatory restrictions could increasingly drive water policy in California. If environmental flow allocations were altered to reflect overall drier conditions, the impacts of climate change would be shared more equitably among water uses (and water scarcity would be commonplace).

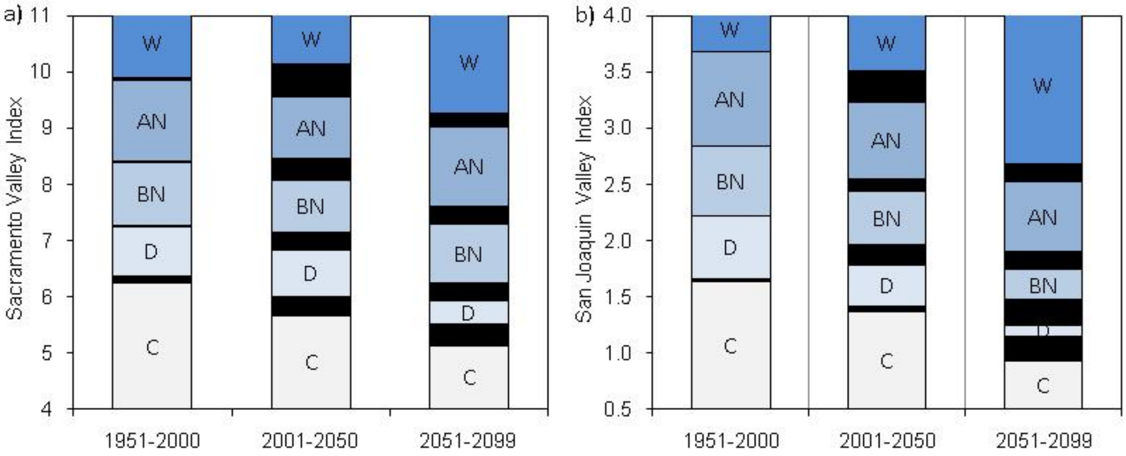

Figure 9. Modeled Water Year Classification Thresholds Using Historical Percentages of Years Per Category Where Black Bands Show Uncertainty Between A2 and B1 Projections for (a) SVI and (b) SJI (Note scale change between figures. C is critically dry, d is dry, BN is below normal, AN is above normal, and W is wet.)

Numerous peer-reviewed papers exist about developing environmental flows (Tharme 2003; Arthington et al. 2006; Acreman and Dunbar 2004), but the quality, accuracy, and utility of the SVI and SJI indices for these purposes have yet to be extensively studied. It is important to improve understanding of how much water is needed to maintain and enhance aquatic and riparian ecosystems in the Bay Delta, but it makes little sense to rigorously study environmental flow allocations, while arbitrarily setting water year classification thresholds. Failing to recognize how probabilities of year types may shift with climate change introduces error and uncertainty into the long-term regulatory stability emphasized by the SWRCB's flow decisions, FERC's relicensing, and NMFS's Biological Opinions. These mechanisms may not preserve the hydrologic variability needed to maintain ecosystem health with the potential of 16 to 21 percent more dry and critically dry years in the SVI, and 28 to 30 percent more dry and critically dry years in the SJI by the end of the twenty-first century. Quiring (2009) has described methods to develop objective index thresholds, and future research should focus on improving understanding of how much water is needed for environmental protection, while considering the WYT framework underpinning environmental flow objectives.

In a changing climate, attention should also be given to the relative frequency of each WYT and how that affects the hydrologic variability necessary to maintain aquatic ecosystems. Aquatic ecosystems depend on hydrologic variability to preserve function and integrity (Richter et al. 1997). In undeveloped river systems, aquatic and riparian ecosystems must respond to climate change. However, in developed systems, water managers have some responsibility to maintain ecological functions and health of downstream aquatic and riparian systems. In a future where more than half of all years are designated as critically dry, larger instream flows may be warranted to manage hydrologic variability if we are to maintain existing ecosystems. The listing of additional species as threatened or endangered could also increase environmental flow requirements.

However, preserving the historical distribution of species and ecosystems, for which environmental flow requirements were developed, may not be the ecosystems we choose to manage for in the future (Lund et al. 2010). As a society, we like to preserve ecosystems that we are accustomed to, although that may not be realistic in a future with severe climate change (Hanak et al. 2011). Future conditions, as well as unanticipated events such as invasions of exotic species, collapse of food webs, or changing migration barriers, could all threaten the historical distribution of ecosystems. Changing frequencies of WYTs may present an opportunity to openly recognize that ecosystems are already heavily managed and to more explicitly decide what ecosystems, functions, and species we opt to manage for.

Water resources will likely be managed more tightly in coming decades. It is in the interest of the public trust to implement a mechanism or formal process to adapt WYT classification and to promote flexibility in water policy for meeting environmental flow needs. In past years, the SWRCB has generally reopened hearings to revise Bay Delta quality standards every 15 to 20 years. This may provide a mechanism to revise WYT thresholds and environmental protection standards, and to correct water allocation imbalances between environmental flows, consumptive water users in the Bay Delta, and water exports south of the Bay Delta. This also implicitly hands these types of adaptive management decisions to SWRCB, perhaps without a more structured revision process. The SWRCB could also potentially review the timing of inflows with climate change and adjust seasonal weighting of runoff to preserve WYT integrity.

It makes little sense to rely on a water allocation framework that assumes climatic stationarity when research repeatedly indicates climatic and hydrologic change is anticipated for California (Cayan et al. 2008; Null et al. 2010; Knowles and Cayan 2002). Climate, WYT, and water allocation decision-making are interrelated. WYT thresholds should be reevaluated at SWRCB hearings (or a similar forum), and WYT thresholds should be periodically revised to maintain WYT classification integrity with the historic division of WYT. Infrastructure or policy improvements that reduce water demands, increase water reliability, or improve water quality (for both people and ecosystems) in light of anticipated hydroclimate changes should be made a priority today to hedge future water scarcity and environmental decline. Finally, in light of existing water scarcity (there is already not enough water to meet Bay Delta exports for the three driest year types), the state must commit to environmental protection while recognizing that the distribution of species, habitats, and ecosystem services may shift with climate change.

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Glossary

A2	A greenhouse gas emissions scenario set forth by the Intergovernmental Panel on Climate Change in its Special Report on Emissions Scenarios. A2 is characterized by a world of independently operating, self-reliant nations, continuously increasing population, and regionally oriented economic development.
ANOVA	Analysis of variance, a standard statistical analysis technique
B1	A greenhouse gas emissions scenario set forth by the Intergovernmental Panel on Climate Change in its Special Report on Emissions Scenarios, published in 2000. B1 depicts a more globally integrated and ecologically friendly world than A2.
CO_2	Carbon dioxide, a contributor to global climate change
CVP	Central Valley Project, the federal-level water project in California
FERC	Federal Energy Regulatory Commission
GCM	Global circulation model, also known as global climate model
GHG	Greenhouse gas—a gas such as carbon dioxide or methane that contributes to global climate change
maf	Million acre-feet, a unit of measure of water flow
NMFS	National Marine Fisheries Service
SJI	San Joaquin Valley Index, or the "60-20-20 Index"; used to quantify runoff in the San Joaquin Valley Basin
SRES	Special Report on Emissions Scenarios, a publication of the Intergovernmental Panel on Climate Change; see http://ipcc.ch/ipccreports/sres/emission/index.php?idp=0
SVI	Sacramento Valley Index, also known as the "Four River Index" and the "40-30-30 Index"; used to quantify runoff in the Sacramento Valley Basin

SWP	State Water Project
SWRCB	State Water Resources Control Board
USFWS	U.S. Fish and Wildlife Service
VIC	Variable Infiltration Capacity, the name of a hydrologic model used in this study
WYT	Water year type—classification of a 12-month period of precipitation as average, above-normal, below-normal, etc.