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Future Peak Streamflow Analytics for the Skagit River

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Abstract

Within the Upper Skagit River, the Ross, Diablo, and Gorge dams are operated by Seattle City Light for hydropower generation, flood risk reduction, fish management, and recreational opportunities. The Skagit Climate Science Consortium (SC^2) study projects how streamflow will change with a warming climate under RCPs 4.5 and 8.5. The main issue identified with the SC^2 study is that some model outputs are inconsistent with previous research. The objective of this study is to identify the reason(s) for the shifts in climate change impacts on flood projection in the SC^2 study. This study checks whether valid data was used within the SC^2 study, validates model results, recalculates flood statistics for various return frequencies, and identifies the changes in the annual peak flow dates of the occurrence. This study found that the SC^2 study used data based on calendar years and calculated flood statistics with Log-Pearson III using non-bias-corrected data, resulting in lower future flood risks as compared to historical risks. By using bias-corrected data, water years, and GEV-L moments, which fit annual peak data better than Log-Pearson III, results show that flood risks will increase throughout the 21st century and will be higher than historical flood risks for time periods 2025-2074 and 2050-2099, especially under RCP 8.5. This study found that peak flows will occur earlier throughout the 21st century, which is consistent with results from previous studies. This study will be used in the process of relicensing the Skagit Hydroelectric project.

Introduction

The Skagit River basin originates in southwestern British Columbia, flows through the North Cascades National Park, and ends in the Puget Sound lowlands (see Figure 1), draining a total area of approximately 3,115 square miles (Lee et al., 2016). Major locations within the Skagit River basin include watersheds providing its major tributaries, the Upper Skagit River, the Baker River, the Cascade River, and the Sauk River. The dams in the Upper Skagit River—Ross, Diablo, and Gorge—are operated by Seattle City Light for Seattle's hydropower generation, flood risk reduction, fish management and preservation, and recreational opportunities. Thus, it is vital to understand how the hydrology will transform with climate change along these dams to better educate future dam management. This report does not review the two dams along the Baker River as they are managed by Puget Sound Energy.

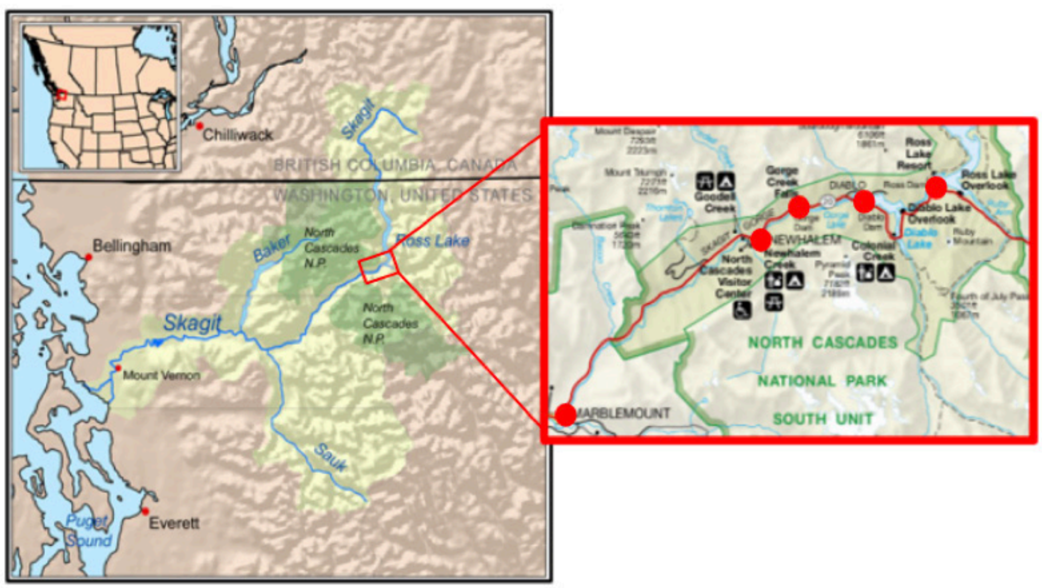


Figure 1 Map of the Upper Skagit River with this study's study sites in red circles (Modified from National Park Service 2021 and Skagit Climate Science Consortium 2015).

The Skagit River basin is currently dominated by transient/mixed rain-snow watersheds, which produce an annual peak flow in winter following the seasonal maximum precipitation and another in late spring/early summer when the stored snowpack melts (Lee et al., 2016; Elsner et al., 2010). At higher elevations in the basin, watersheds are snow-dominated with peak streamflows timed with spring snowmelt. Transient watersheds are specifically susceptible to climate change, as a warming climate relates to decreased snowfall and faster snowmelt earlier in the season, resulting in increased winter flows and decreased summer flows (Elsner et al., 2010; Lee et al., 2016).

A previous study found that the 100-year flood in the Skagit River near Mount Vernon is projected to increase by 40% under unregulated conditions (i.e., no dam operations) by 2100 (Lee et al., 2016). As a result of climate change, the large Skagit River basin is likely to shift towards rain-dominant watershed conditions by 2100 due to warming temperatures, which would decrease the amount of precipitation as snowfall (Lee & Hamlet, 2011). This would result in a single annual peak flow near Mount Vernon following the seasonal maximum precipitation (Lee & Hamlet, 2011). The shift from multiple annual peak streamflows to a single annual peak streamflow is associated with increases in major floods and decreased hydropower generation during non-peak times (Lee et al., 2016). The relicensing of Seattle City Light's dams ensures their future use as tools of flood control via discharging water from dams at later intervals, thus reducing the potential flood impacts, which may prove useful against potential increases in major floods in the Skagit River basin.

The Skagit Climate Science Consortium (SC^2) is a nonprofit comprised of research scientists in collaboration with all levels of government, as well as local tribes, universities, and residents, to "assess, plan, and adapt to climate related impacts" (Skagit Climate Science Consortium, 2015). The SC^2 supported a project to provide projections of how streamflow and water availability will change with a warming climate to better prepare for water management in the future. The project modeled the future streamflow projections of 20 sites within the Skagit River basin under low and high greenhouse gas emissions scenarios (Representative Concentration Pathways [RCPs] 4.5 and 8.5, respectively). It was completed by the University of Washington Civil and Environmental Engineering Department with support from Seattle City Light, Swinomish Indian Tribal Community, and the Sauk-Suiattle Indian Tribe partnering with SC^2.

An unexpected finding identified within the results of the SC^2 study is that some model outputs were inconsistent with previous research. For example, under unregulated conditions, the SC^2 project reports a 6% average decrease and a 4% average increase in the 100-year flood flow (i.e., a flood event with a 1% probability of exceedance for any given year) by the 2050-2099 time period under RCPs 4.5 and 8.5, respectively. Previous research reported an average 40% increase in the 100-year flood flow under the A1B scenario, an older emission scenario in between RCPs 4.5 and 8.5 (Hamlet et al., 2013). The SC^2 study's results were inconsistent because the magnitude of percent changes found were much lower than expected, and the study projected a decrease in flood flow under the high greenhouse gas emissions scenario (RCP 8.5), which was also unexpected when compared to previous research.

The main objective of this study is to identify the reason(s) for the shifts in climate change impacts on flood projection in the existing SC^2 project. To analyze the expected changing hydrology of the Skagit River basin due to climate change, this study:

1. Checks whether valid data was used within the SC^2 project,
2. Validates the SC^2 project's model results by comparing simulated historical annual peak flows with observed flows, and
3. Checks if there is any error in SC^2's flood statistics data by recalculating the flood statistics for various return frequencies.

Background

The SC^2 project used the Distributed Hydrology Soil and Vegetation Model (DHSVM) at 150 m grid resolution to analyze the impacts of climate change on floods in the Skagit River basin, with a 50 m resolution in Thunder Creek and Cascade River subbasins to assess their notable glacial ice cover with an integrated glacial melt model (Bandaragoda et al., 2015; Bandaragoda et al., 2019).

The projections by the SC^2 study were based on 10 Global Climate Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) used to model future climate projections under low and high greenhouse gas emission scenarios, RCPs 4.5 and 8.5, respectively (Bandaragoda et al., 2015). The 10 GCMs used were bcc-csm1-1-m, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk-3-6-0, HadGEM2-CC365, HadGEM2-ES365, IPSL-CM5A-MR, MIROC5, and NorESM1-M. The CMIP5 GCMs are part of standard experimental methods used within the climate modeling field to project future atmospheric and ocean circulation, precipitation, and more under different greenhouse gas emissions scenarios (World Research Climate Programme, 2020).

The GCMs used by the SC^2 study were statistically downscaled with Multivariate Adaptive Constructed Analogs (MACA) methods (Abatzoglou and Brown, 2012). In a 2019 update to the project, Bandaragoda et al. (2019) developed a hybrid bias correction for the input meteorology that used weather data from Cooperative Observer network (COOP) stations and the regional Weather Research Forecast (WRF) model to remove the cold bias-gridded data product in the observationally based Livneh dataset (Livneh et al., 2013). The hybrid data bias correction was applied to reconstruct both historical and future meteorologic data such as temperature and precipitation. Streamflow data, outputs from DHSVM, were also bias-corrected when at least 20 years of observed streamflow data was available (Bandaragoda et al., 2015; Bandargoda et al., 2019). The SC^2 study chose 1962-2009 as the historical period for future comparisons, while all GCMs used 1950-2005 as historical simulations and 2006-2099 as future projections. Flood statistics for different return frequencies were obtained using Log-Pearson Type III distributions in the SC^2 project.

Methods

Observed and Bias-Corrected Streamflow

The SC^2 study projected changes in monthly streamflow and flood statistics for 20 sites in the Skagit River basin, as shown in Table 1. Streamflow data was bias-corrected when observed unregulated flow data overlapped at least 20 years with the historical time period of 1962-2009. For sites not affected by dam operations, observational data was obtained from the United States Geological Survey (USGS). For the sites in the Upper Skagit River whose streamflow was affected by dam operations, Seattle City Light (SCL) provided observed unregulated streamflow data. This report uses bias-corrected flows for all analysis unless mentioned otherwise.

This study checks USGS IDs for all SC^2 sites, the length of observation, and magnitude of bias-corrected monthly streamflow data to see whether the bias corrections were correctly conducted.

Table 1 Twenty streamflow sites used in the SC^2 Study. The table lists USGS ID, water years (Oct-Sept) of observed monthly streamflow data, sources of observation and the status of bias-correction.

Site Name in SC^2 Website	USGS ID	Water Years	Source of Observation	Bias-Corrected
Upper Skagit River				
Ross	12175000	1989-2020	SCL	Yes
Thunder Creek	12175500	1931-2020	USGS	Yes
Diablo	12176500	1989-2020	SCL	Yes
Gorge	12177700	1989-2020	SCL	Yes
Newhalem to Marblemount*	12178000	1909-2020	SCL	Yes
	12181000	1987-2020		
Illabot	12184500	1983-1984		No
Bacon	12180000	1944-1949		No
Jackman Creek	12190000	1944-1946		No
Finney Creek	12194500	1945-1947		No
Red Cabin Creek	-			No
Cascade River				
Cascade River	12182500	2007-2020		No
Jordan Creek	12183500	1945-1946		No
Sauk River				
White Chuck	12186500	1920-1921	USGS	Yes (Incorrect)

North Fork Sauk River	12185000	1918-1919		No
South Fork Sauk River	12185500	1918-1920 1928-1930		No
Sauk River near Sauk	12189500	1912-2020	USGS	Yes
Sauk River at Darrington	12187500	1915-1925 1929-1931 2021-2015		No
Sauk River above White Chuck	12186000	1918-2020	USGS	No (Incorrect)
Sauk River above Clear Creek	12187000	1910-1913		No
Big Creek	12188500	1944-1946		No

*Newhalem to Marblemount is the incremental flow between the sites of Newhalem and Marblemount, which represents side stream contributions and not the mainstream Skagit.

Annual Peak Flows and Flood Statistics

Extreme daily high flows with 2, 5, 10, 20, 50 and 100-year recurrence intervals were projected in the SC^2 study. To validate their results, this study recalculates the extreme values and compares these values with those found in the SC^2 study for four sites: the Ross, Gorge, and Diablo dams and the Newhalem to Marblemount site, as shown in Figure 1. This was achieved through analyzing annual peak flows and their respective fits to historical data, overall flood trend analysis, cumulative distribution functions, and flood statistics. Additional analysis includes calculating the shifts in annual peak flow timing and normalizing streamflow data.

<u>Annual Peak Flows</u>

The maximum daily peak flows were selected for each water year (Oct-Sept) since cool season (Oct-Mar) precipitation affects the water availability of the following spring and summer seasons (Apr-Sept). Annual peak flows from this study were compared with those in the SC^2 study.

<u>Time-Series of Annual Peak Flows</u>

To evaluate the model's performance, time-series of annual peak flows from historical simulations were compared with those obtained from observed data. R^2 values were computed using Pearson methods to assess how closely the historical simulations correlate with the observed data.

Trend Analysis

The SC^2 study generally shows an increase in flood risks over time, though lower flood risks were projected for some flood frequencies (e.g., 100-year flood under RCP 4.5 for Ross). Thus, 50-year average annual peaks for 2000-2049, 2025-2074, and 2050-2099 were plotted on top of the time-series of annual peak flows to see if similar trends to the SC^2 results would be produced.

Cumulative Distribution Functions (CDF)

To create cumulative distribution function (CDF) plots, the annual peak flows were ranked highest to lowest by flow magnitude, a quantile was assigned to each value using an unbiased quantile estimator (Stedinger et al., 1993), and the ranked flows were plotted as a function of the quantile.

CDFs were used to validate the model's performance by comparing CDFs of the historical simulated values with those from the observed data. Additionally, CDFs were used to estimate changes in flow magnitude under climate change. Similar to the SC^2 project, this study used 50-year periods (2000-2049, 2025-2074, 2050-2099) as the future time periods and 1962-2009 as the historical time period.

Flood Statistics

To estimate flood statistics, Generalized Extreme Value distributions using the L-moment method (GEV-L moments) were applied to the ranked annual peak flows since this distribution is known to perform well for extreme data (Hosking, 1990). Flood statistics were calculated for the 2, 5, 10, 20, 50, and 100-year return frequencies for the historical and future periods. Percent changes in flood statistics were calculated by comparing the flood statistics of each future period (2000-2049, 2025-2074, 2050-2099) to the selected historical period. The historical period of 1962-2009 was chosen as it was used within the SC^2 project and an additional historical period of 1962-2005 was chosen because the historical periods for all GCMs ended in 2005, and thus 2006- 2009 consist of future simulations. The fit of the GEV-L moments was examined in historical simulations and the selected future simulations by comparing values from GEV-L moments with CDFs of annual peaks. Since the SC^2 project used Log-Pearson Type III distributions to get their flood statistics, a similar method was used to check the fitness of Log-Pearson III values to the annual peaks.

On the SC^2 website, it is not noted whether percent changes under the extreme floods are based on bias-corrected or non-bias-corrected data. This study checks whether bias-corrected or non-bias-corrected data was used to report the percent change values for the floods by recalculating the percent changes for the 100-year flood based on both datasets and comparing the statistics to those reported on the SC^2 website.

Changes in Annual Peak Timing

The dates of occurrence and magnitude of daily peaks were plotted to evaluate the impacts of climate change on the timing of the annual peak flows. The average date of annual peak occurrences was calculated for both a historical time period (1962-2005) and three future time periods (2000-2049, 2025-2074, and 2050-2099) for each GCM under RCPs 4.5 and 8.5.

Normalized Streamflow

The monthly average streamflows are normalized flows (*xNormalized*) based on the historical flows using the following equation (Loukas, 2020):

$$X_{Normalized} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

Where x is the monthly average streamflow for each month, X_{max} is the maximum from the historical monthly average streamflow (e.g., X_{max} was the average July flow for the Ross Dam site), while X_{min} was set to 0, as shown in (Equation 1).

Results

Errors in SC² Data

Annual Peak Flows

When this study's annual peaks were compared with those used in the SC^2 project, we noticed that the SC^2 project published their data using calendar years (CY) instead of water years (WY). As an example, Table 2 shows annual peaks and occurrence dates that were used in the SC^2 project and in this study for years 1989-1991 for Ross Dam. The SC^2 project reports 15,963 cubic feet per second (cfs) as the peak flow for the year 1989. Since it occurred on 12/4/1989, it does not correspond to the water year 1989, which is defined as October 1st of the previous year to September 30th of the following year (e.g., Water Year 1989 = 10/1/1988 - 9/30/1989), but instead corresponds to the water year 1990 or calendar year 1989. The peaks of 33,518 and 14,167 cfs occurred on 11/10/1990 and 6/29/1991, respectively. Since both dates are in the water year 1991 (10/1/1990-9/30/1991), the higher peak of the two values (33,518 cfs) is the peak flow of water year 1991. Unlike the SC^2 project, this study chose to use annual peak flows based on water years throughout this study as it is more consistent with other research in this field.

Table 2 An example of SC^2 reported annual peak flows versus this study's calculated peak flows for 1989-1991.

Year	SC^2 Reported		This Study	
	Peak Flow (cfs)	Date of Flow	Peak Flow (cfs)	Date of Flow
1989	15,963	12/4/1989	10,137	5/ 8/1989
1990	33,518	11/10/1990	15,963	12/4/1989
1991	14,167	6/29/1991	33,518	11/10/1990

Bias-Corrected Flows

In Table 1, the bias correction for the White Chuck and Sauk River Above White Chuck sites is labeled as incorrect. The streamflow at the White Chuck site is labeled as bias-corrected on the SC^2 website, but it only has 1 full water year of observed flows from USGS. The Sauk River Above White Chuck site has more than 30 years of observed USGS data, but it is not labeled as bias-corrected on the SC^2 website. Additionally, bias-corrected monthly flows at White Chuck more closely match USGS monthly flows from the Sauk River above the White Chuck site.

Historical Simulations

CDFs and time-series of annual peak flows show that all GCMs under RCPs 4.5 and 8.5 except for the CCSM4 model have the same values for annual peak flow during 1983-2009 (see Figures 2 and 3). The CCSM4 model under RCPs 4.5 and 8.5 produce the same values during 1962-2005 and begin to differ from one another in 2006 (see Figure 3). Additionally, daily streamflow data was examined to assess any differences in the data, but the same results were produced (note that this data is not shown in this study because daily datasets are thousands of rows long). In other words, all GCMs except for the CCSM4 model produce the same daily flow data under both RCPs for the historical period (1962-2009), which is an unexpected result. This was consistent across all four sites included in this study: the Ross, Diablo, and Gorge dams, as well as the Newhalem to Marblemount site. Bandaragoda et al. (2015) & Bandaragoda et al. (2019) did not mention that they used historical simulations from each GCM, but instead that Livneh data was used as the historical simulation data. Since bias correction was applied to remove cold bias in Livneh data, it is likely an error that the CCSM4 data has different historical values for 1962-2009 than the nine other GCMs. Thus, this study uses the data from one historical simulation as our historical simulated dataset, which is assumed to be the Livneh dataset.

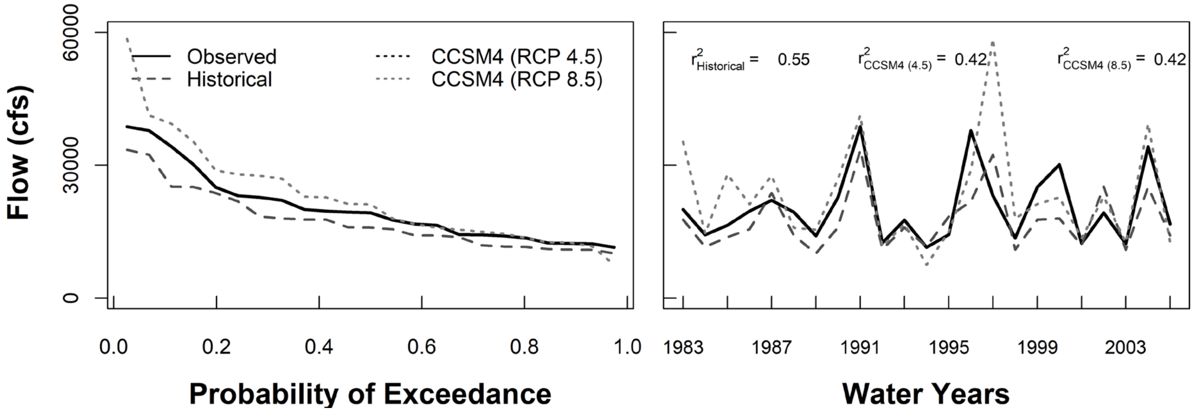


Figure 2 CDFs (left) and time-series of annual peak flows (right) for WY 1983-2005 for Ross Dam. "Historical" refers to historical simulations from all GCMs under RCPs 4.5 and 8.5 except CCSM4. "Observed" refers to observed annual peak flows. Note that the CCSM4 model under RCPs 4.5 and 8.5 produce the same values until WY 2005.

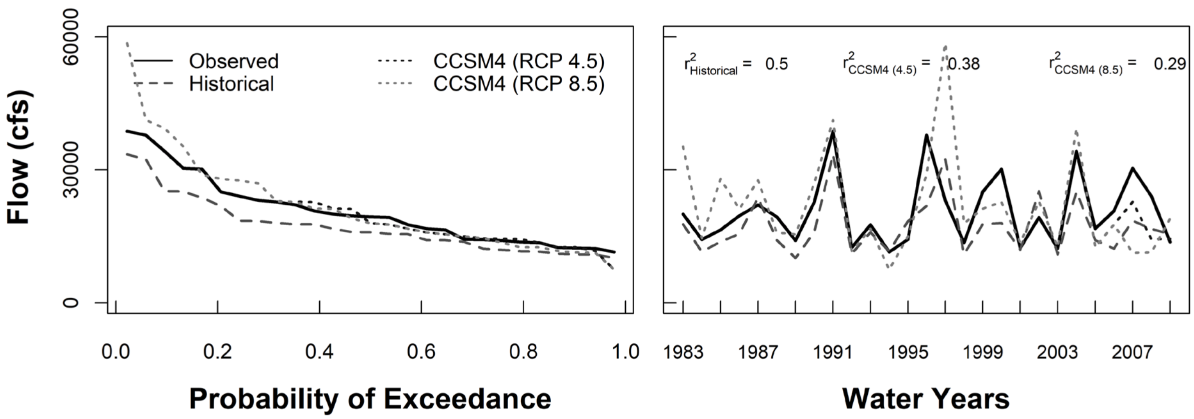


Figure 3 As shown in Figure 2, except for WY 1983-2009.

Validating the Model

The model reproduced the observed annual peaks reasonably well but was generally lower than observations for the Ross Dam site for both historical periods 1983-2005 and 1983- 2009 (R^2 = 0.55 and 0.50, respectively). However, there is some disagreement in the time-series for some years and CDFs for simulated historical flows were lower than those for observed ones (see Figures 2 and 3). Similar pattens were observed for the Diablo, Gorge, and Newhalem to Marblemount site (R^2 = 0.56, 0.56, and 0.77, respectively; see Figures 4 and 5).

Including the years 2006-2009 in the historical period decreased R^2 values by 0.05 as compared to the observation for Ross Dam (see Figures 2 and 3), which reflects the fact that the years 2006-2009 are the future simulations in all GCMs (not historical simulations). Thus, it would be more reasonable to use 1962-2005 as the historical baseline rather than 1962-2009.

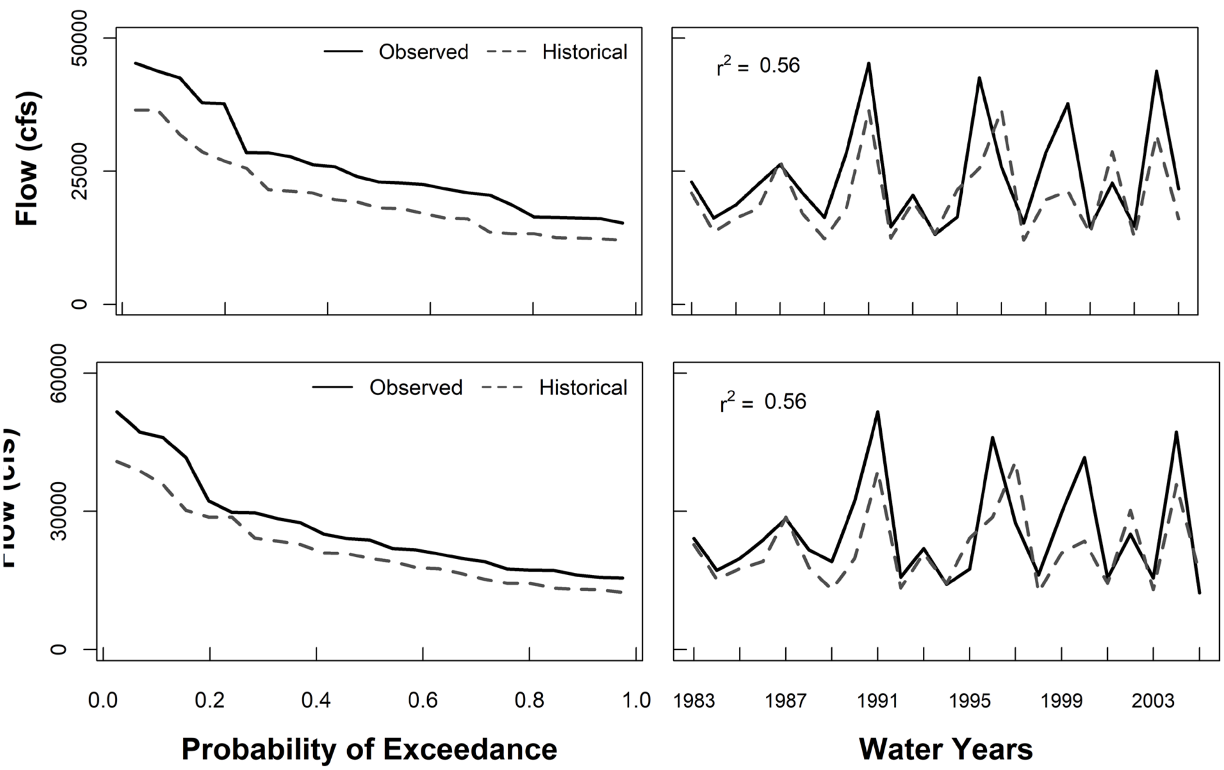


Figure 4 As shown in Figure 2, except for Diablo Dam (top) and Gorge Dam (bottom) under WY 1983-2005.

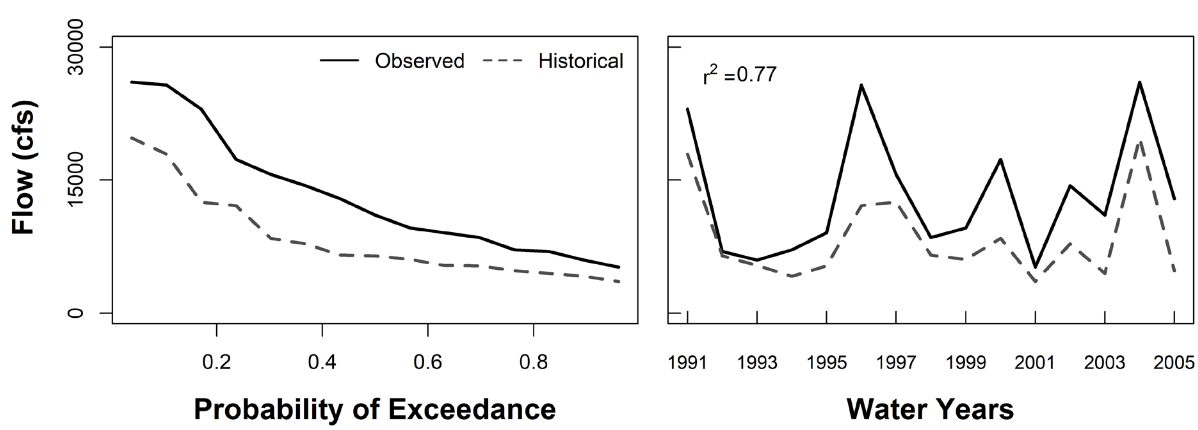


Figure 5 As shown in Figure 2, except for the Newhalem to Marblemount site under WY 1991-2005.

CDFs of Historical vs Future Simulations

Figures 6 and 7 show CDFs of historical and future simulations up to a probability of exceedance of 0.5 (i.e., high-frequency floods), as the GCMs have no major differences after 0.5 for all future time periods and this project focuses on the extreme lower-frequency floods (2-year to 100-year floods).

Based on Figure 6, the 100-year flood for Ross Dam under RCP 4.5 during the 2000-2049 time period is expected to be similar to or slightly higher than historical observed data, as approximately half of the GCMs show lower CDFs than the historical data, when the probability of exceedance is 0.01. This contrasts with the SC^2 reported value of a 12% average decrease in the 100-year flood under RCP 4.5 by the 2000-2049 time period. Under RCP 8.5, the SC^2 project reports a 15% average decrease in the 100-year flood for Ross Dam by the 2000-2049 time period, and based on Figure 6, it is also expected that the 100-year flood for Ross Dam will be lower than the historical flood as most GCMs show lower CDFs than the historical data. During 2025-2074, the 100-year floods under both RCPs for Ross Dam are expected to be slightly higher than the historical flood since the majority of GCMs show higher CDFs than the historical data, which contrasts to the SC^2 reported values of 8% and 16% average decreases in 100-year flood by the 2025-2074 time period under RCPs 4.5 and 8.5, respectively (see Figures 6 and 7). Under both RCPs for Ross Dam, the 100-year floods for the 2050-2099 time period are expectedto be higher than the historical flood (Figures 6 and 7), which contrasts to the SC^2 reported values of a 6% average decrease and a 4% average increase in the 100-year flood under RCPs 4.5 and 8.5, respectively.

Similar results were found for the Diablo and Gorge Dam sites, as Figures 6 and 7 show increased 100-year flood risks as compared to the historical data for all time periods, while the SC^2 project generally reports decreasing or narrowly increasing percent changes in the flood risks.

For the Newhalem to Marblemount site, all models and time periods show higher values for the 100-year flood than the historical data. For all time periods under both RCPs, the 100-year flood is expected to increase as compared to the historical flood (Figures 6 and 7). This is in agreement with the SC^2 reported average percent change values for the 2025-2074 and 2050-2099 time periods under both RCPs (12% ~ 40%). However, this contrasts with the SC^2 reported percent change values for the 2000-2049 time period of -8% and -13% (under RCPs 4.5 and 8.5, respectively). For all sites, the highest flood risks are expected during the 2050-2099 time period under RCP 8.5.

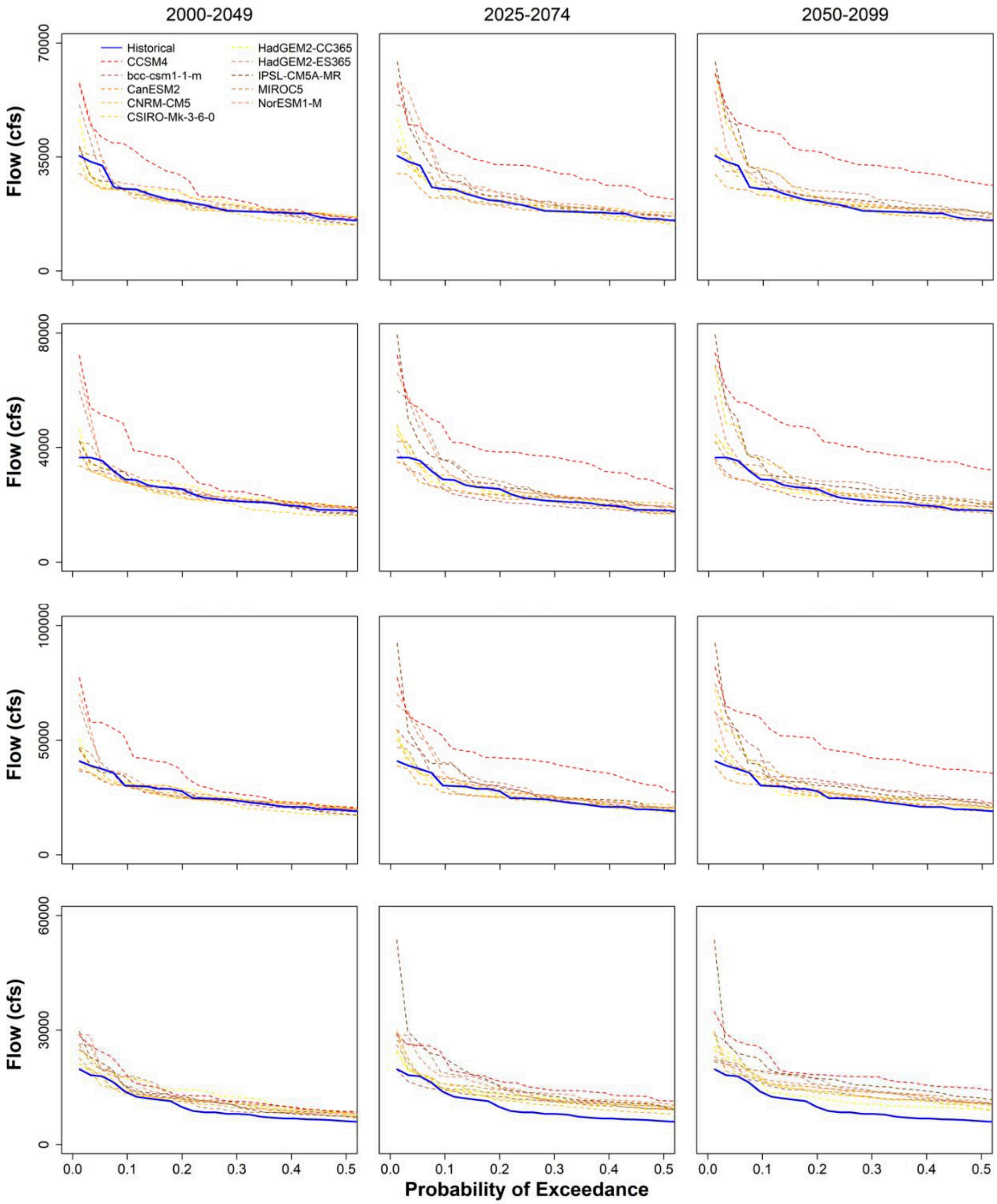


Figure 6 CDFs of annual peak flows during 2000-2049, 2025-2074, and 2050-2099 from all GCMs as compared to the historical simulation from 1962-2009 for Ross Dam (top), Diablo Dam (second), Gorge Dam (third), and the Newhalem to Marblemount site (bottom) under RCP 4.5. Note that the probability of exceedance is only plotted until 0.5, as this project focuses on the extreme floods.

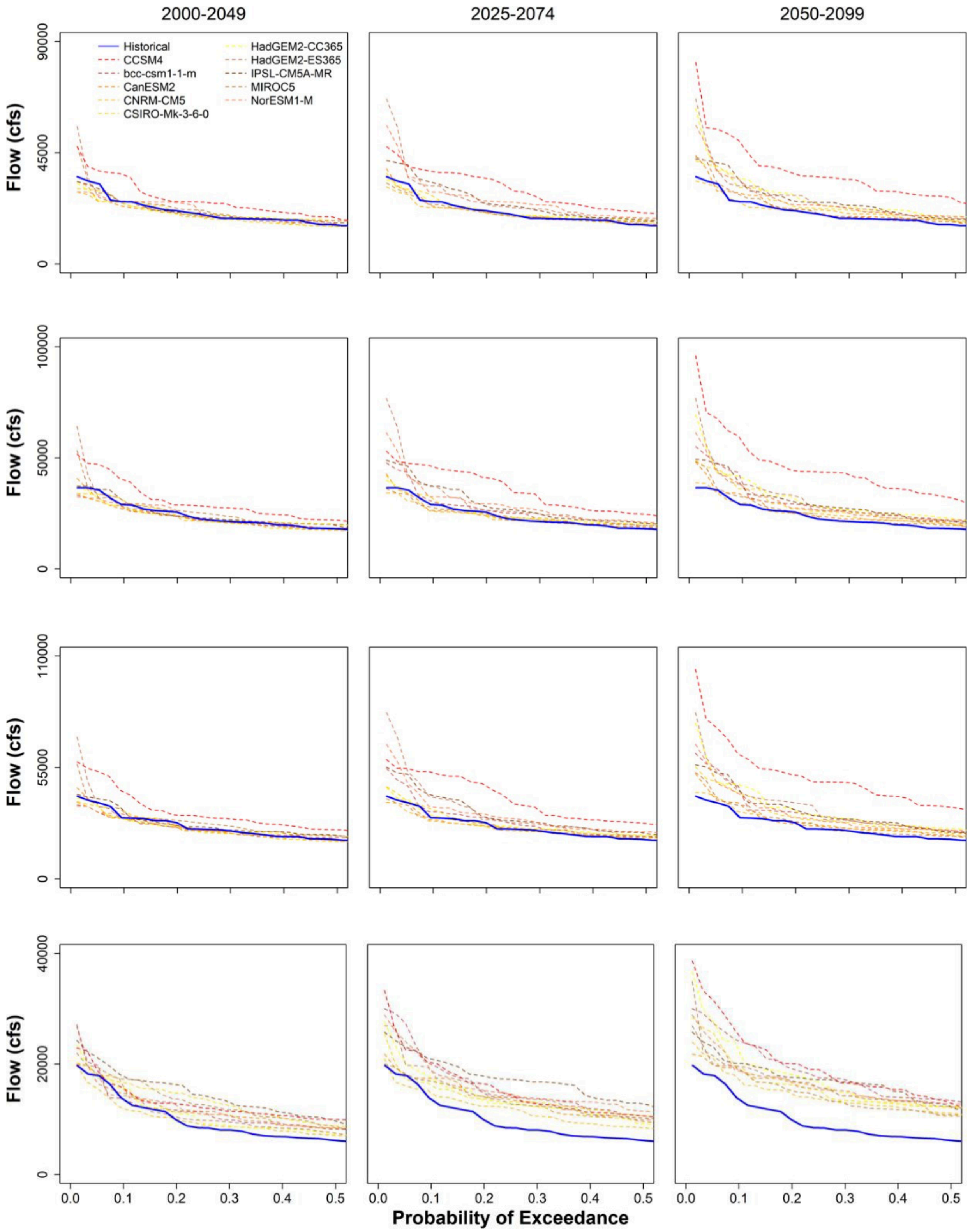


Figure 7 As in Figure 6, except under RCP 8.5.

Trend Analysis

To analyze the trends in flood risks, the 50-year averages of annual peaks for three different time periods under RCPs 4.5 and 8.5 were plotted in Figures 7 and 8 for the Newhalem to Marblemount site. Under RCP 4.5, 9 GCMs show a steady increase in flow throughout the century, while one model shows a slight increase, and therefore floods are expected to increase in magnitude as time continues (see Figure 8). Under RCP 8.5, 10 GCMs show increases in flow throughout the century (see Figure 9), so floods are expected to increase substantially in magnitude throughout the years.

For Ross Dam under RCP 4.5, four models show increasing trends in flow throughout the century, while four models show that flow stayed relatively consistent, and two models show a slight decreasing trend in flow (see Figure A1). Thus, flood risks are expected to slightly increase or stay relatively similar throughout the century under RCP 4.5. Under RCP 8.5, nine models show increases in flow throughout the century, while one model shows that flow stayed relatively consistent, so floods are expected to increase substantially throughout the century (see Figure A2).

Under RCP 4.5 for Diablo Dam, five models show increasing trends in flow throughout the century, while four models show that flow stayed relatively consistent, and one model shows a slight decreasing trend in flow, so flood risks are expected to slightly increase or stay relatively similar throughout the century (see Figure A3). Under RCP 8.5, nine models show an increasing trend, while one model shows that flow stayed relatively consistent, so floods are expected to increase substantially throughout the century (see Figure A4).

Under RCP 4.5 for Gorge Dam, five models show increasing trends in flow throughout the century, while five models show that flow stayed relatively consistent, so flood risks are expected to slightly increase or stay relatively similar throughout the century (see Figure A5). Under RCP 8.5, nine models show increasing trends, while one model shows that flow stayed relatively consistent, so floods are expected to increase substantially throughout the century (see Figure A6).

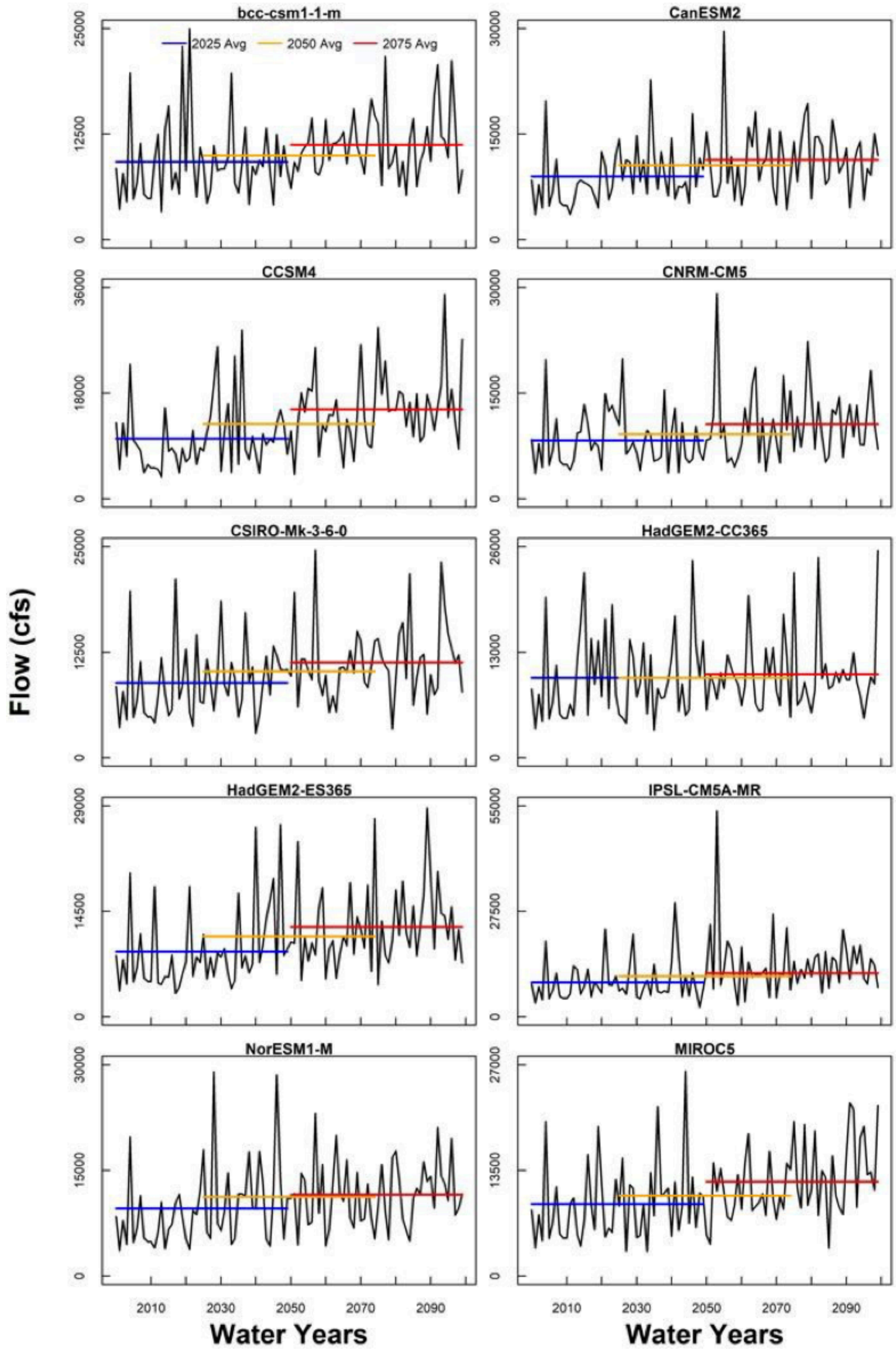


Figure 8 Time-series of future annual peak simulations with 50-year averages for 2000-2049, 2025-2074, and 2050-2099 time periods under RCP 4.5 for the Newhalem to Marblemount site.

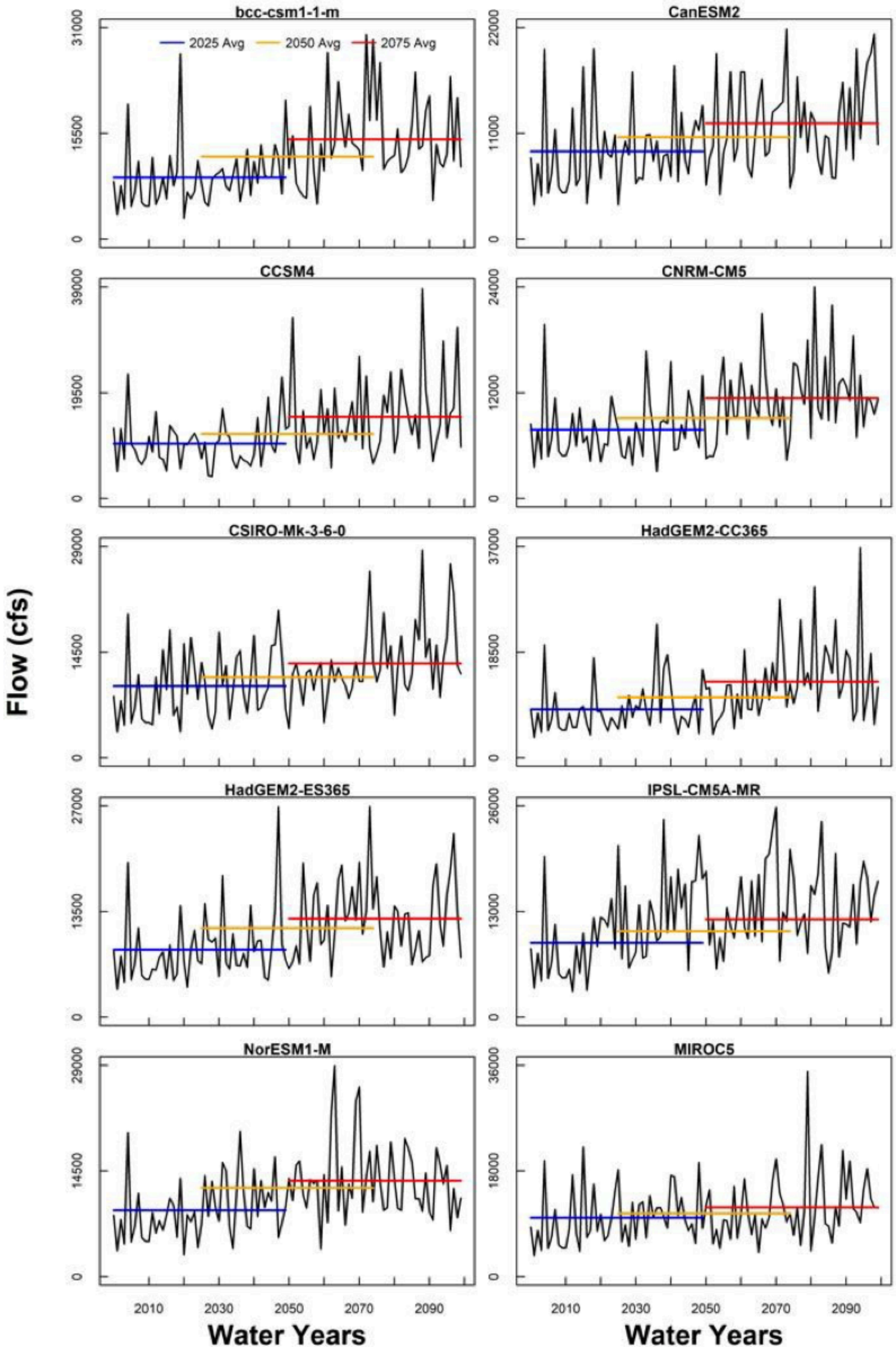


Figure 9 As shown in Figure 8, except under RCP 8.5.

Percent Changes in Floods

The mean percent changes in flood magnitudes for Ross Dam from the SC^2 project showed small negative values or positive values for the high-frequency floods (i.e., 2-year floods; - 2~15% and 5-year floods; -2~16%), meaning future 2-year and 5-year floods will be higher than or similar to historical floods (see Table 3). However, the mean percent changes decrease as the return frequency value increases (e.g., from 10-year to 100-year floods). For example, the mean percent changes in the 100-year floods for Ross Dam were negative (-16 to -6%), except for one value for the 2050-2099 time period under RCP 8.5 (4%), meaning future flood risks will be lower than the historical floods except for the flood for the 2050-2099 time period under RCP 8.5 (see Table 3).These trends were also apparent for the Diablo Dam and Gorge Dam sites (see Tables 4-6).

For the Newhalem to Marblemount site, the mean percent change values from the SC^2 project report negative values for all floods during the 2000-2049 time period, and positive values for all floods during the 2025-2074 and 2050-2099 time periods (see Table 6). However, this study projects positive percent change values for all floods under both RCPs for all time periods, except for the 100-year flood during the 2000-2049 time period under RCP 8.5 (-5% and -3%, based on the historical time periods of 1962-2005 and 1962-2009, respectively). However, the percent change values for the 2000-2049 time period are lower in magnitude than the -13% reported from SC^2, meaning this study projects higher flood risks than SC^2 (see Table 6).

This study shows higher flood risks than the SC^2 project for all flood return frequencies for the 2025-2074 and 2050-2099 time periods, under both historical periods 1962-2005 and 1962- 2009. This study's mean values are either positive and consistently higher than those previously reported in the SC^2 project, or negative and lower in magnitude than those previously reported in the SC^2 project (see Tables 3-6; see Figures 10-13 for visual examples). The results show that flood risks will increase throughout the 21st century and will be higher than historical flood risks for time periods 2025-2074 and 2050-2099, especially under RCP 8.5 (see Figures 10-13 and Figures B1-I5). Median values were also calculated for each return frequency and time period, as it is more representative of the data than a mean value alone due to high maximum percent change values.

Table 3 Percent change values for 2, 5, 10, 20, 50, and 100-year floods for Ross Dam. "SC²"columns show Mean (Min; Max) and "This Study" columns show Mean/Median (Min; Max). Blue correlates to a negative percent change mean value, while salmon correlates to a positive percent change value.

Freq.	**Water Years**	**RCP 4.5**			**RCP 8.5**		
		SC²	**This Study**		**SC²**	**This Study**	
		Baseline of 1962-2009	Baseline of 1962-2009	Baseline of 1962-2005	Baseline of 1962-2009	Baseline of 1962-2009	Baseline of 1962-2005
2-yr	2000-2049	0% (-4%; +4%)	+2%/+2% (-7%; +11%)	+3%/+2% (-7%; +16%)	-2% (-9%; +11%)	+3%/+2% (-3%; +17%)	+3%/+2% (-3%/+16%)
	2025-2074	+2% (-4%; +7%)	+6%/+3% (-5%; +43%)	+6%/+3% (-5%; +42%)	+2% (-10%; +20%)	+10%/+7% (0%; +33%)	+9%/+6% (0%; +32%)
	2050-2099	+5% (-2%; +15%)	+12%/+7% (-2%; +71%)	+12%/+7% (-2%; +70%)	+15% (+2%; +27%)	+19%/+16% (+5%; +60%)	+18%/+15% (+5%; +59%)
5-yr	2000-2049	-2% (-12%; +2%)	+3%/0% (-9%; +24%)	+2%/-1% (-11%; +22%)	+3% (-8%; +10%)	-4%/-8% (-18%; +29%)	+1%/-1% (-6%; +23%)
	2025-2074	0% (-11%; +17%)	+10%/+6% (-11%; +57%)	+8%/+5% (-12%; +55%)	+7% (-6%; +21%)	+11%/+6% (-17%; +47%)	+10%/+4% (-2%; +43%)
	2050-2099	+3% (-9%; +18%)	+14%/+9% (-8%; +76%)	+12%/+7% (-9%; +73%)	+16% (+8%; +28%)	+25%/+28% (-26%; +90%)	+22%/+19% (+5%; +75%)
10-yr	2000-2049	-5% (-18%; +3%)	+3%/0% (-10%; +32%)	+2%/-2% (-12%; +30%)	-6% (-16%; +12%)	-1%/-4% (-13%; +29%)	-1%/-3% (-10%; +25%)
	2025-2074	-2% (-17%; +22%)	+11%/+4% (-13%; +57%)	+9%/+2% (-15%; +54%)	-2% (-19%; +21%)	+12%/+4% (-10%; +46%)	+10%/+2% (-7%; +44%)
	2050-2099	+1% (-13%; +19%)	+14%/+9% (-12%; 71%)	+12%/+7% (-14%; +68%)	+13% (-4%; +28%)	+28%/+26% (-3%; +88%)	+23%/+21% (+1%; +80%)
20-yr	2000-2049	-7% (-24%; +5%)	+4%/-1% (-12%; +41%)	+2%/-3% (-14%; +38%)	-9% (-22%; +14%)	+1%/-2% (-8%; +27%)	-4%/-6% (-14%; +26%)
	2025-2074	-4% (-23%; +26%)	+12%/+3% (-15%; +54%)	+9%/0% (-17%; +51%)	-7% (-27%; +21%)	+12%/+4% (-5%; +46%)	+9%/+2% (-12%; +43%)
	2050-2099	-1% (-16%; +20%)	+14%/+8% (-15%; +63%)	+11%/+6% (-17%; +60%)	+10% (-9%; +29%)	+26%/+23% (+3%; +84%)	+25%/+23% (-5%; +84%)
50-yr	2000-2049	-10% (-32%; +7%)	+5%/-2% (-19%; +52%)	+2%/-4% (-21%; +49%)	-13% (-30%; +17%)	+2%/0% (-5%; +25%)	-6%/-11% (-20%; +25%)
	2025-2074	-6% (-31%, +31%)	+13%/+4% (-19%; +46%)	+10%/+1% (-21%; +42%)	-12% (-36%; +21%)	+12%/+6% (0%; +45%)	+9%/+4% (-19%; +43%)
	2050-2099	-4% (-19%, +22%)	+13%/+8% (-19%; +51%)	+10%/+5% (-21%; +47%)	+7% (-16%; +29%)	+23%/+20% (+7%; +78%)	+22%/+25% (-28%; +85%)

100-yr	2000-2049	-12% (-38%; +9%)	+5% / -3% (-24%; +62%)	+2% / -6% (-27%; +57%)	-15% (-35%; +19%)	-6% / -12% (-23%; +29%)	-9% / -15% (-25%; +25%)
	2025-2074	-8% (-36%; +34%)	+13% / +5% (-24%; +53%)	+10% / +2% (-26%; +28%)	-16% (-43%; +21%)	+11% / +8% (-23%; +58%)	+8% / +5% (-25%; +53%)
	2050-2099	-6% (-22%; +24%)	+13% / +9% (-22%; +49%)	+10% / +6% (-24%; +45%)	+4% (-22%; +29%)	+32% / +30% (-18%; +90%)	+28% / +26% (-20%; +85%)

Table 4 As shown in Table 3, except for Diablo Dam.

Freq.	**Water Years**	**RCP 4.5**			**RCP 8.5**		
		SC2	**This Study**		**SC2**	**This Study**	
		Baseline of 1962-2009	Baseline of 1962-2009	Baseline of 1962-2005	Baseline of 1962-2009	Baseline of1962-2009	Baseline of 1962-2005
2-yr	2000-2049	0% (-4%; +5%)	+1% / +1% (-8%; +11%)	+2% / 0% (-9%; +17%)	+3% (-8%; +10%)	+3% / +1% (-4%; +18%)	+2% / 0% (-5%; +17%)
	2025-2074	+2% (-4%; +8%)	+7% / +2% (-5%; +47%)	+6% / +1% (-6%; +46%)	+7% (-5%; +21%)	+10% / +7%(0%; +36%)	+9% / +6% (-1%; +35%)
	2050-2099	+5% (+2%; +15%)	+13% / +7% (-3%; +80%)	+12% / +7% (-3%; +79%)	+16% (+8%; +28%)	+21% / +18% (+7%; +70%)	+20% / +17% (+6%; +69%)
5-yr	2000-2049	-2% (-12%; +3%)	+3% / +2% (-9%; +26%)	+2% / 0% (-11%; +23%)	-2% (-9%; +11%)	+3% / 0% (-5%; +26%)	+1% / -1% (-6%; +24%)
	2025-2074	0% (-11%; +18%)	+11% / +7% (-10%; +64%)	+9% / +5% (-12%; +62%)	+2% (-10%; +20%)	+13% / +7%(0%; +50%)	+11% / +6% (-2%; +47%)
	2050-2099	+3% (-8%; +18%)	+16% / +9% (-7%; +88%)	+14% / +7% (-9%; +84%)	+15% (+2%; +28%)	+26% / +22% (+8%; +91%)	+24% / +20% (+6%; +88%)
10-yr	2000-2049	-5% (-18%; +4%)	+5% / +2% (-9%; +37%)	+3% / 0% (-11%; +34%)	-5% (-16%; +12%)	+2% / -1% (-7%; +30%)	0% / -3% (-9%; +27%)
	2025-2074	-2% (-17%; +23%)	+13% / +5% (-12%; +67%)	+11% / +3% (-14%; +64%)	-2% (-18%; +21%)	+14% / +7% (-4%; +53%)	+12% / +5% (-6%; +50%)
	2050-2099	+1% (-12%; +19%)	+17% / +9% (-10%; +84%)	+15% / +7% (-12%; +80%)	+13% (-3%; +28%)	+29% / +25% (+5%; +100%)	+27% / +23% (+3%; +96%)
20-yr	2000-2049	-7% (-24%; +4%)	+7% / +2% (-9%; +49%)	+4% / 0% (-11%; +46%)	-9% (-22%; +14%)	+2% / -3% (-10%; +33%)	0% / -5% (-11%; +30%)
	2025-2074	-4% (-23%; +27%)	+15% / +4% (-13%; +66%)	+12% / +2% (-14%; +62%)	-7% (-27%; +21%)	+15% / +7% (-9%; +54%)	+12% / +5% (-11%; +51%)
	2050-2099	-1% (-16%; +21%)	+17% / +8% (-13%; +77%)	+15% / +6% (-15%; +73%)	+11% (-9%; +29%)	+32% / +29%(0%; +105%)	+29% / +27% (-2%; +100%)

50-yr	2000-2049	-10% (-32%; +6%)	+9% / +1% (-15%; +68%)	+7% / -1% (-17%; +64%)	-13% (-30%; +16%)	+1% / -3% (-15%; +36%)	-2% / -5% (-16%; +33%)
	2025-2074	-6% (-30%; +31%)	+17% / +4% (-16%; +60%)	+14% / +2% (-18%; +57%)	-12% (-36%; +21%)	+15% / +10% (-15%; +53%)	+13% / +7% (-17%; +50%)
	2050-2099	-4% (-20%; +24%)	+18% / +8% (-16%; +65%)	+15% / +6% (-18%; +62%)	+7% (-16%; +30%)	+33% / +34% (-7%; +108%)	+30% / +31% (-9%; +104%)
100-yr	2000-2049	-13% (-37%; +7%)	+10% / 0% (-31%; +83%)	+8% / -2% (-33%; +79%)	-16% (-33%; +17%)	0% / -3% (-18%; +37%)	-2% / -5% (-20%; +34%)
	2025-2074	-8% (-35%; +33%)	+18% / +6% (-20%; +55%)	+16% / +3% (-22%; +52%)	-17% (-43%; +20%)	+16% / +12% (-20%; +67%)	+13% / +9% (-22%; +64%)
	2050-2099	-5% (-22%; +28%)	+19% / +10% (-17%; +56%)	+16% / +7% (-19%; +53%)	+4% (-21%; +29%)	+38% / +37% (-12%; +109%)	+35% / +34% (-14%; +105%)

Table 5 As shown in Table 3, except for Gorge Dam.

Freq.	**Water Years**	**RCP 4.5**			**RCP 8.5**		
		SC2	**This Study**		**SC2**	**This Study**	
		Baseline of 1962-2009	Baseline of1962-2009	Baseline of 1962-2005	Baseline of 1962-2009	Baseline of 1962-2009	Baseline of 1962-2005
2-yr	2000-2049	0% (-4%, +5%)	+2% / +2% (-8%; +13%)	+2% / 0% (-9%; +18%)	+3% (-8%; +10%)	+3% / +1% (-4%; +20%)	+2% / 0% (-5%; +18%)
	2025-2074	+2% (-3%; +8%)	+9% / +5% (0%; +50%)	+8% / +4% (-1%; +48%)	+7% (-5%; +21%)	+12% / +9% (+1%; +39%)	+10% / +8% (0%; +38%)
	2050-2099	+5% (-2%; +15%)	+18% / +11% (+1%; +84%)	+16% / +10% (0%; +82%)	+16% (+8%; +30%)	+23% / +22% (+8%; +77%)	+22% / +20% (+7%; +75%)
5-yr	2000-2049	-2% (-11%; +3%)	+3% / +1% (-9% / +26%)	+1% / -1% (-11%; +24%)	-2% (-9%; +11%)	+3% / 0% (-5%; +28%)	+1% / -2% (-7%; +26%)
	2025-2074	+1% (-10%; +18%)	+14% / +11%(-3%; +66%)	+12% / +8% (-5%; +63%)	+3% (-10%; +21%)	+14% / +9%(0%; +53%)	+12% / +7% (-2%; +50%)
	2050-2099	+3% (-7%; +18%)	+21% / +13%(-1%; +90%)	+18% / +11% (-3%; +87%)	+16% (+3%; +29%)	+29% / +24% (+9%; +97%)	+26% / +22% (+6%; +93%)
10-yr	2000-2049	-4% (-17%; +4%)	+5% / +2% (-8%; +37%)	+3% / -1% (-10%; +34%)	-5% (-16%; +12%)	+3% / -2% (-7%; +32%)	0% / -4% (-9%; +29%)
	2025-2074	-1% (-16%; +24%)	+16% / +11%(-6%; +68%)	+13% / +8% (-8%; +64%)	-2% (-18%; +21%)	+16% / +8% (-4%; +57%)	+13% / +6% (-6%; +54%)
	2050-2099	+1% (-11%; +20%)	+22% / +17%(-4%; +86%)	+19% / +15% (-6%; +82%)	+14% (-3%; +29%)	+32% / +27% (+8%; +104%)	+29% / +24% (+6%; +99%)

20-yr	2000-2049	-7% (-24%; +4%)	+6% / +2% (-9%; +49%)	+4% / 0% (-11%; +46%)	-9% (-22%; +13%)	+2% / -3% (-9%; +35%)	0% / -5% (-11%; +32%)
	2025-2074	-3% (-22%; +27%)	+18% / +10% (-10%; +66%)	+15% / +8% (-12%; +62%)	-6% (-26%; +21%)	+16% / +9% (-9%; +59%)	+14% / +7% (-11%; +55%)
	2050-2099	0% (-15%; +21%)	+23% / +22%(-7%; +79%)	+21% / +19% (-9%; +75%)	+11% (-8%; +30%)	+35% / +31% (+4%; +107)	+32% / +28% (+2%; +103%)
50-yr	2000-2049	-10% (-31%; +6%)	+9% / +2% (-15%; +67%)	+7% / +1% (-17%; +64%)	-13% (-29%; +15%)	+1% / -2% (-15%; +38%)	-1% / -4% (-16%; +35%)
	2025-2074	-6% (-29%; +32%)	+20% / +12% (-16%; +60%)	+18% / +10% (-18%; +57%)	-12% (-35%; +20%)	+17% / +11% (-15%; +61%)	+15% / +9% (-17%; +58%)
	2050-2099	-3% (-19%; +26%)	+25% / +27% (-12%; +67%)	+22% / +24% (-14%; +64%)	+8% (-15%; +30%)	+35% / +36% (-2%; +108%)	+33% / +34% (-3%; +105%)
100-yr	2000-2049	-12% (-37%; +7%)	+11% / +2% (-20%; +82%)	+10% / 0% (-21%; +80%)	-15% (-34%; +17%)	+1% / -1% (-19%; +39%)	-1% / -3% (-20%; +37%)
	2025-2074	-7% (-34%; +34%)	+23% / +14% (-20%; +60%)	+21% / +13% (-22%; +58%)	-16% (-42%; +19%)	+18% / +13% (-20%; +76%)	+17% / +12% (-21%; +74%)
	2050-2099	-4% (-22%; +31%)	+26% / +30% (-17%; +61%)	+24% / +28% (-18%; +58%)	+5% (-20%; +30%)	+41% / +40% (-6%; +108%)	+39% / +38% (-8%; +105%)

Table 6 As shown in Table 3, except for the Newhalem to Marblemount site.

Freq.	**Water Years**	**RCP 4.5**			**RCP 8.5**		
		SC2	**This Study**		**SC2**	**This Study**	
		Baseline of1962-2009	Baseline of 1962-2009	Baseline of1962-2005	Baseline of1962-2009	Baseline of 1962-2009	Baseline of1962-2005
2-yr	2000-2049	-4% (-7%; -2%)	+25% / +27% (+14%;+37%)	+32% / +31% (+14%;+55%)	0% (-5%; +10%)	+32% / +31% (+10%; +55%)	+32% / +31% (+10%; +55%)
	2025-2074	+1% (-7%; +7%)	+51% / +51% (+24%;+85%)	+51% / +51% (+24%;+84%)	+8% (+1%; +33%)	+64% / +63% (+33%;+101%)	+64% / +63% (+33%;+101%)
	2050-2099	+12% (0%; +26%)	+74% / +73% (+43%;+126%)	+74% / +73% (+43%;+126%)	+27% (+13%; +45%)	+90% / +88% (+68%;+112%)	+90% / +88% (+68%;+112%)
5-yr	2000-2049	-4% (-9%; +1%)	+27% / +25% (+13%; +40%)	+26% / +24% (+12%; +39%)	-4% (-12%; +11%)	+28% / +26% (+5%; +55%)	+26% / +25% (+4%; +53%)
	2025-2074	+4% (-8%; +21%)	+47% / +43% (+25%; +80%)	+45% / +41% (+24%; +78%)	+9% (-6%; +40%)	+55% / +53% (+26%; +86%)	+54% / +52% (+25%; +84%)
	2050-2099	+13% (0%; +30%)	+62% / +59% (+34%;+107%)	+61% / +57% (+31%;+105%)	+32% (+15%; +49%)	+77% / +74% (+56%;+105%)	+76% / +72% (+54%;+103%)

10-yr	2000-2049	-5% (-12%; +2%)	+25% / +23%(+9%; +40%)	+23% / +21% (+8%; +38%)	-6% (-16%; +11%)	+21% / +19%(-1%; +47%)	+20% / +17% (-2%; +45%)
	2025-2074	+5% (-10%; +35%)	+40% / +33% (+16%; +70%)	+38% / +32% (+15%; +68%)	+9% (-12%; +43%)	+45% / +44% (+17%; +69%)	+43% / +42% (+16%; +67%)
	2050-2099	+15% (+1%; +38%)	+51% / +44% (+27%; +89%)	+49% / +42% (+25%; +86%)	+35% (+16%; +57%)	+65% / +60% (+42%; +99%)	+63% / +57% (+40%; +96%)
20-yr	2000-2049	-6% (-15%; +2%)	+22% / +23%(+4%; +39%)	+20% / +21% (+2%; +36%)	-8% (-20%; +13%)	+14% / +12%(-6%; +36%)	+12% / +10% (-8%; +34%)
	2025-2074	+7% (-12%; +50%)	+32% / +25%(+2%; +77%)	+30% / +22% (0%; +74%)	+10% (-18%; +44%)	+34% / +36% (+8%; +54%)	+32% / +34% (+6%; +51%)
	2050-2099	+17% (+1%; +50%)	+38% / +29% (+19%; +78%)	+36% / +27% (+17%; +73%)	+37% (+15%; +66%)	+52% / +46% (+27%; +91%)	+49% / +44% (+25%; +88%)
50-yr	2000-2049	-7% (-20%; +3%)	+17% / +18%(-4%; +36%)	+14% / +16% (-6%; +33%)	-11% (-25%; +17%)	+5% / +5% (-14%; +21%)	+2% / +3% (-16%; +19%)
	2025-2074	+10% (-13%; +75%)	+22% / +17% (-15%; +83%)	+20% / +15% (-17%; +78%)	+11% (-26%; +45%)	+19% / +24%(-6%; +45%)	+17% / +21% (-7%; +42%)
	2050-2099	+19% (0%; +68%)	+23% / +17%(+2%; +64%)	+20% / +14% (0%; +20%)	+39% (+12%; +80%)	+33% / +27% (+7%; +80%)	+30% / +24% (+5%; +77%)
100-yr	2000-2049	-8% (-24%; +3%)	+13% / +12% (-10%; +33%)	+10% / +9% (-12%; +30%)	-13% (-28%; +21%)	-3% / -3% (-20%; +10%)	-5% / -5% (-21%; +7%)
	2025-2074	+13% (-14%; +96%)	+14% / +11% (-26%; +87%)	+12% / +9% (-28%; +83%)	+12% (-31%; +45%)	+9% / +13% (-15%; +39%)	+6% / +10% (-17%; +35%)
	2050-2099	+22% (-3%; +85%)	+11% / +6% (-9%; +55%)	+9% / +3% (-11%; +51%)	+40% (+10%; +90%)	+22% / +17%(-4%; +71%)	+20% / +14% (-6%; +68%)

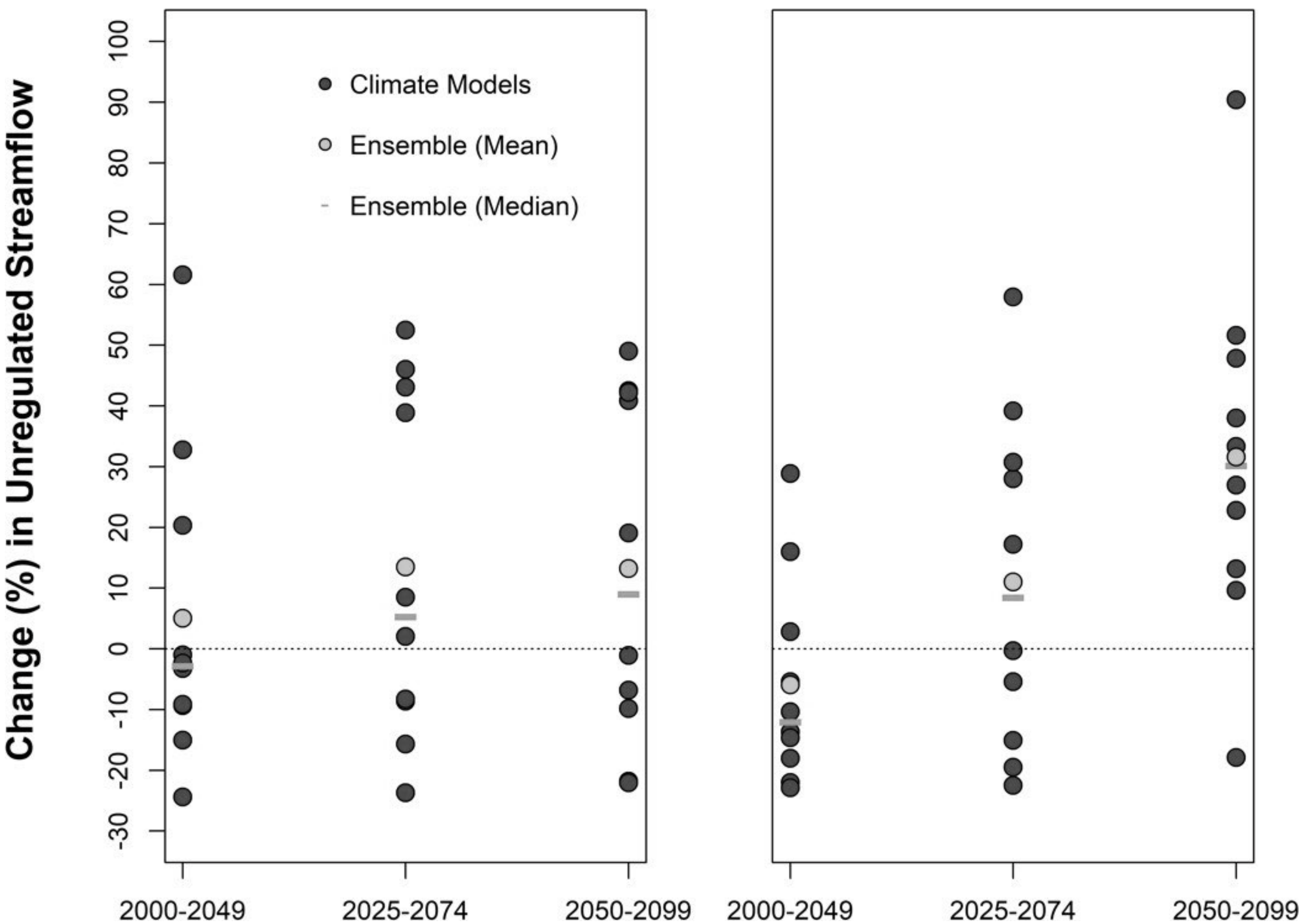


Figure 10 Percent changes for the 100-year flood under RCPs 4.5 (left) and 8.5 (right), with a historical baseline of WY 1962-2005 (top) and 1962-2009 (bottom) for Ross Dam.

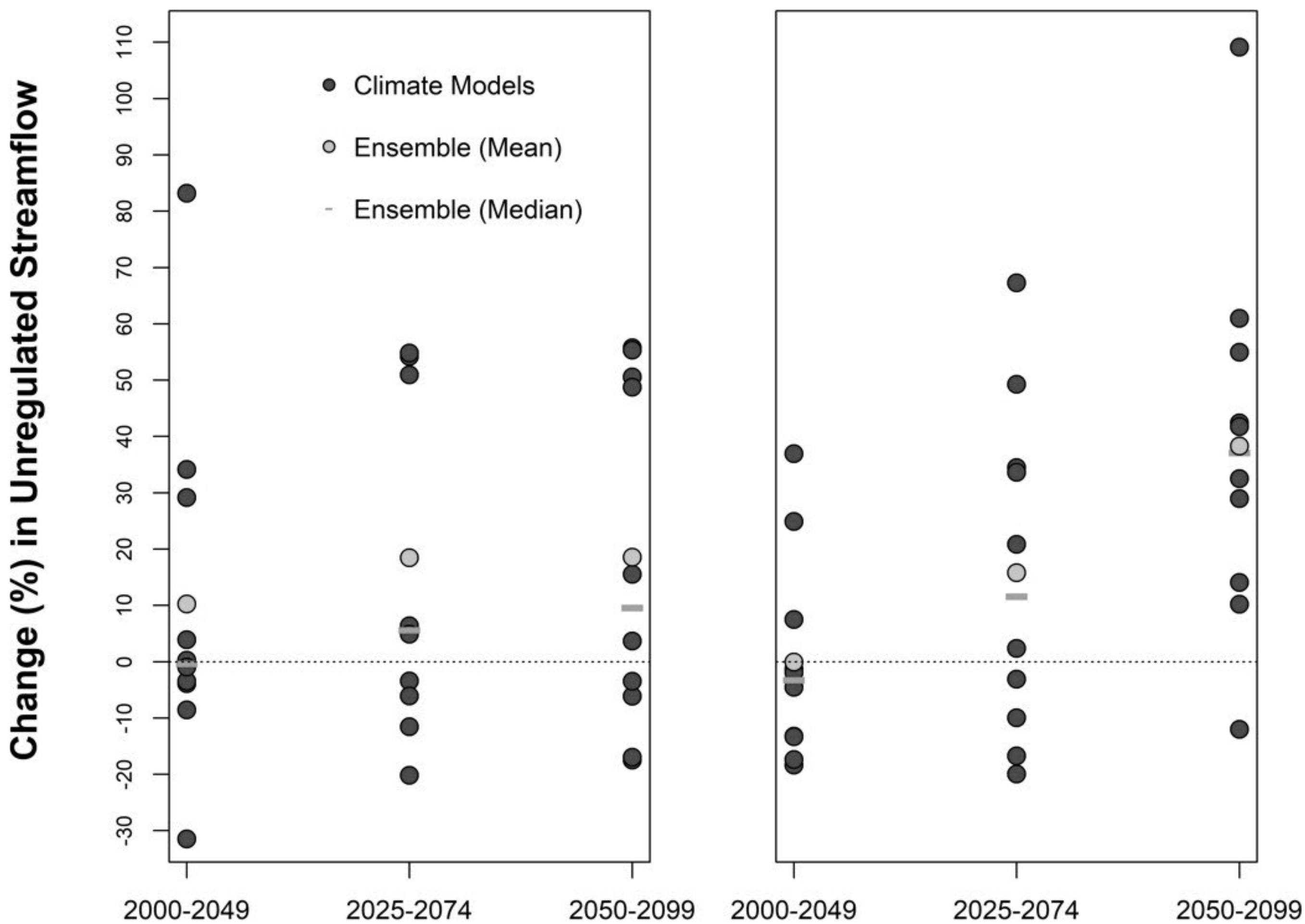


Figure 11 As shown in Figure 10, except for Diablo Dam.

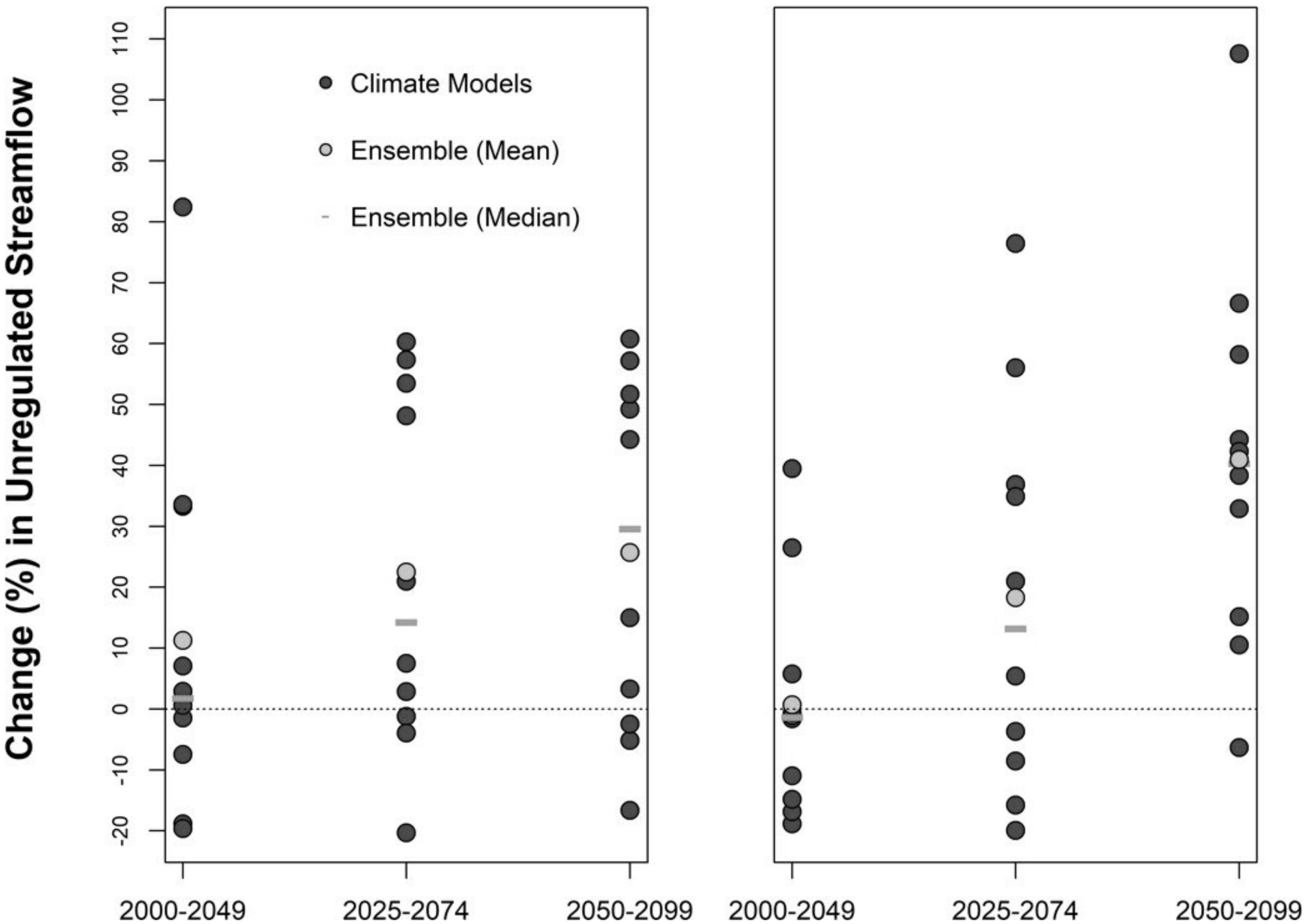


Figure 12 As shown in Figure 10, except for Gorge Dam.

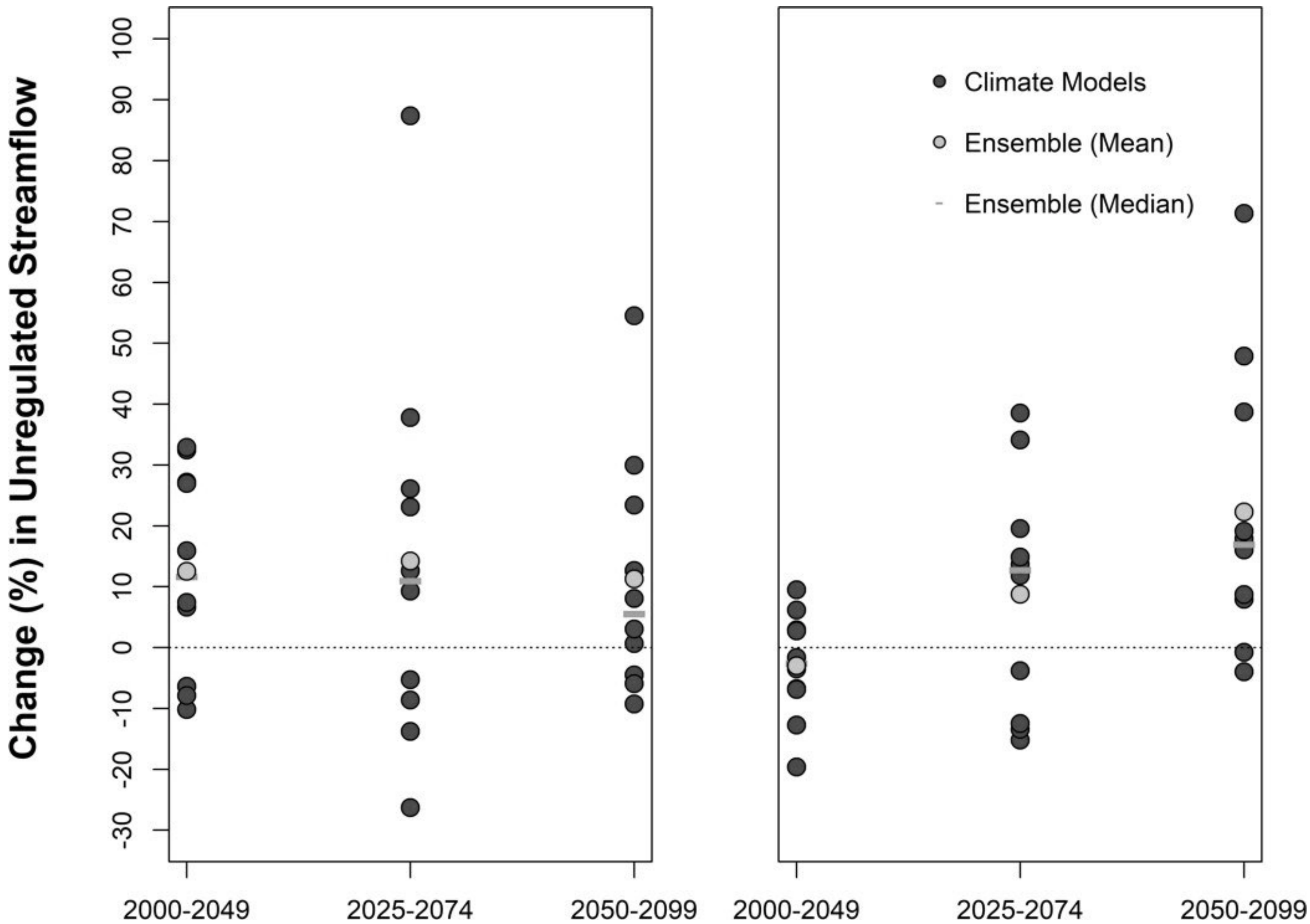


Figure 13 As shown in Figure 10, except for the Newhalem to Marblemount site.

This study produced higher maximum percent change values as compared to those previously reported in the SC[2] project (see Tables 3-6), in which all of these values originated from the CCSM4 model under RCPs 4.5 and 8.5. Figures 14-17 show that extreme statistics using GEV-L moments (red lines) match well with the annual peak CDFs for CCSM4 and the historical simulation dataset (the assumed Livneh dataset) for all sites under RCPs 4.5 and 8.5. Thus, we confirm that there was no error in estimating flood statistics, and our higher maximum percent change values stemming from the CCSM4 model are reasonable.

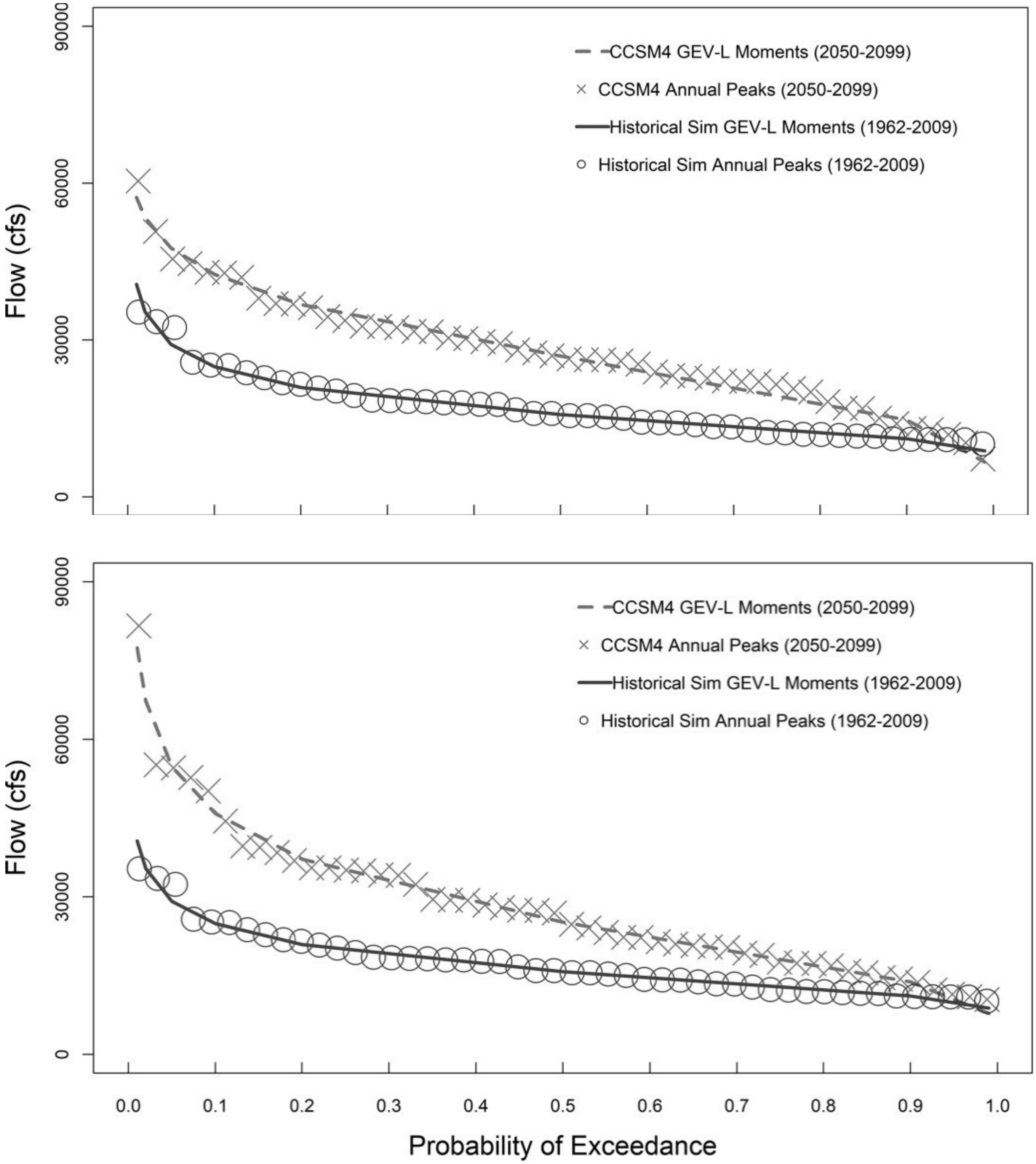


Figure 14 CDF of GEV-L Moments and annual peak flows from the CCSM4 model (red) and historical simulation data (blue) under RCP 4.5 (top) and RCP 8.5 (bottom) for Ross Dam.

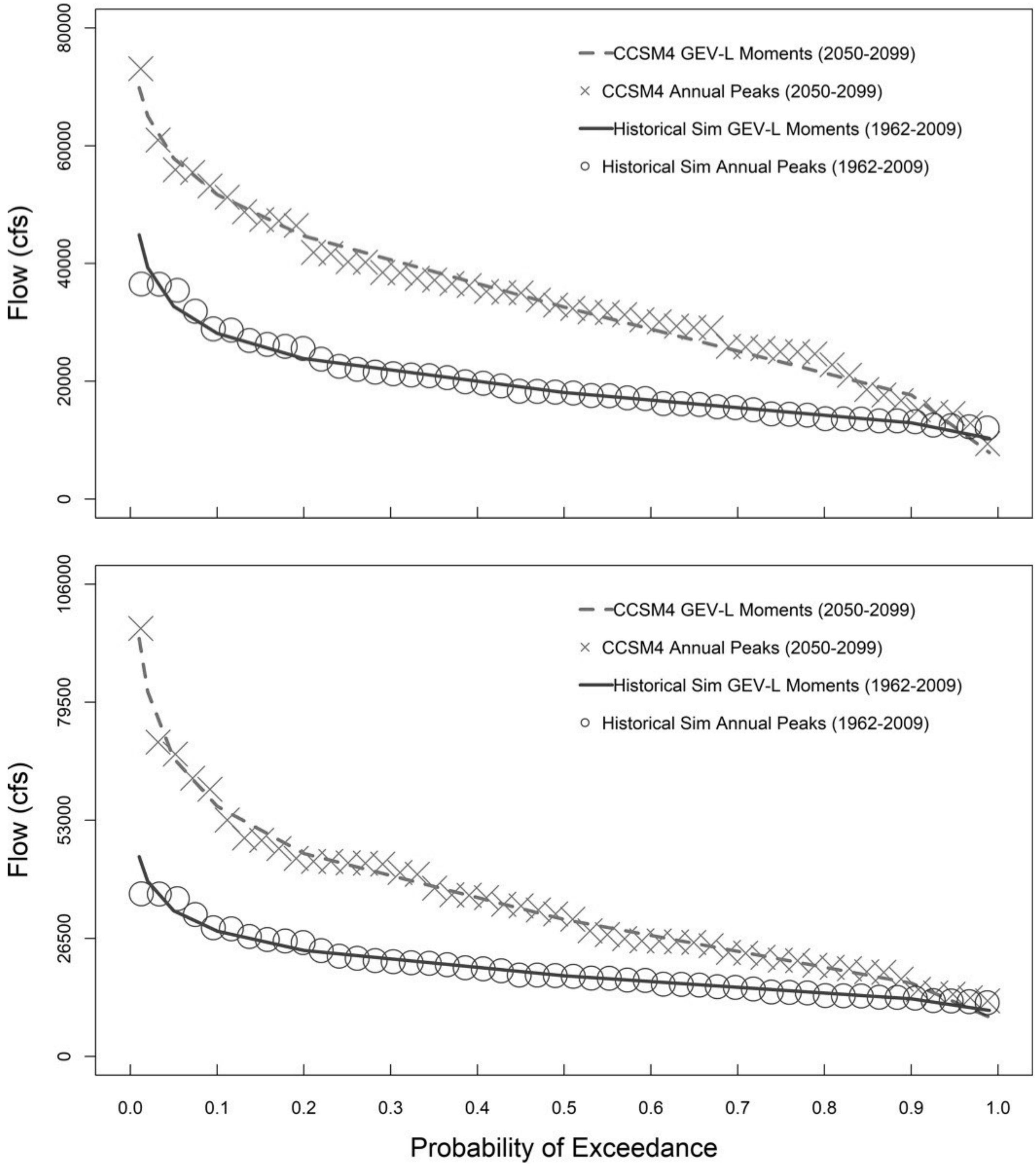


Figure 15 As shown in Figure 14, except for Diablo Dam.

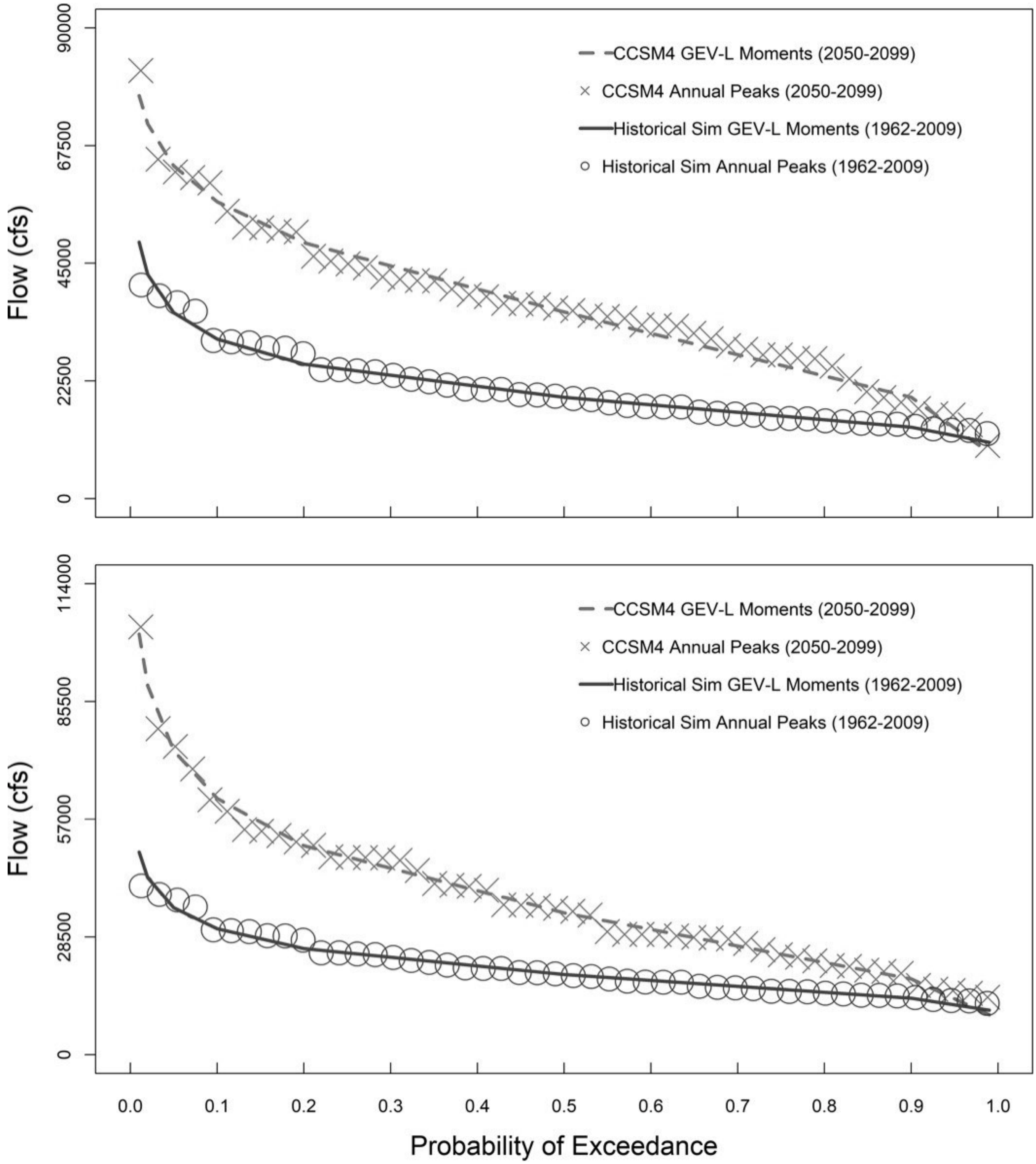
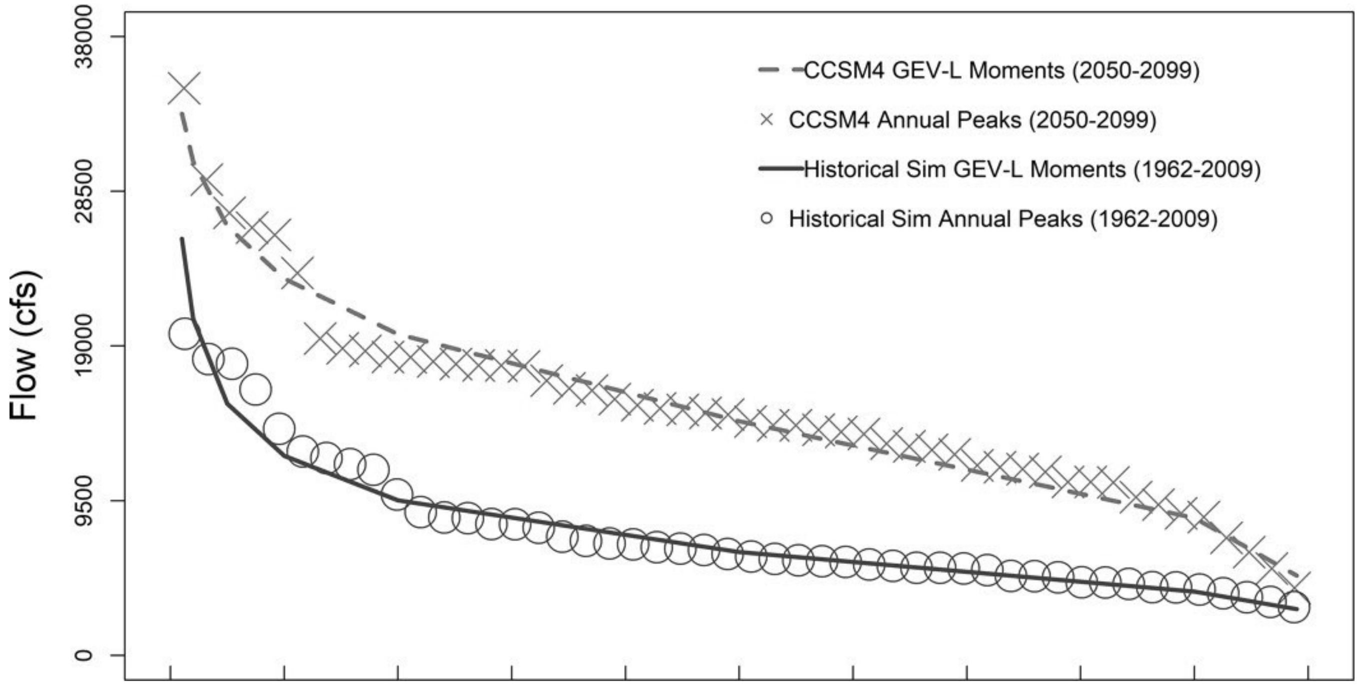


Figure 16 As shown in Figure 14, except for Gorge Dam.



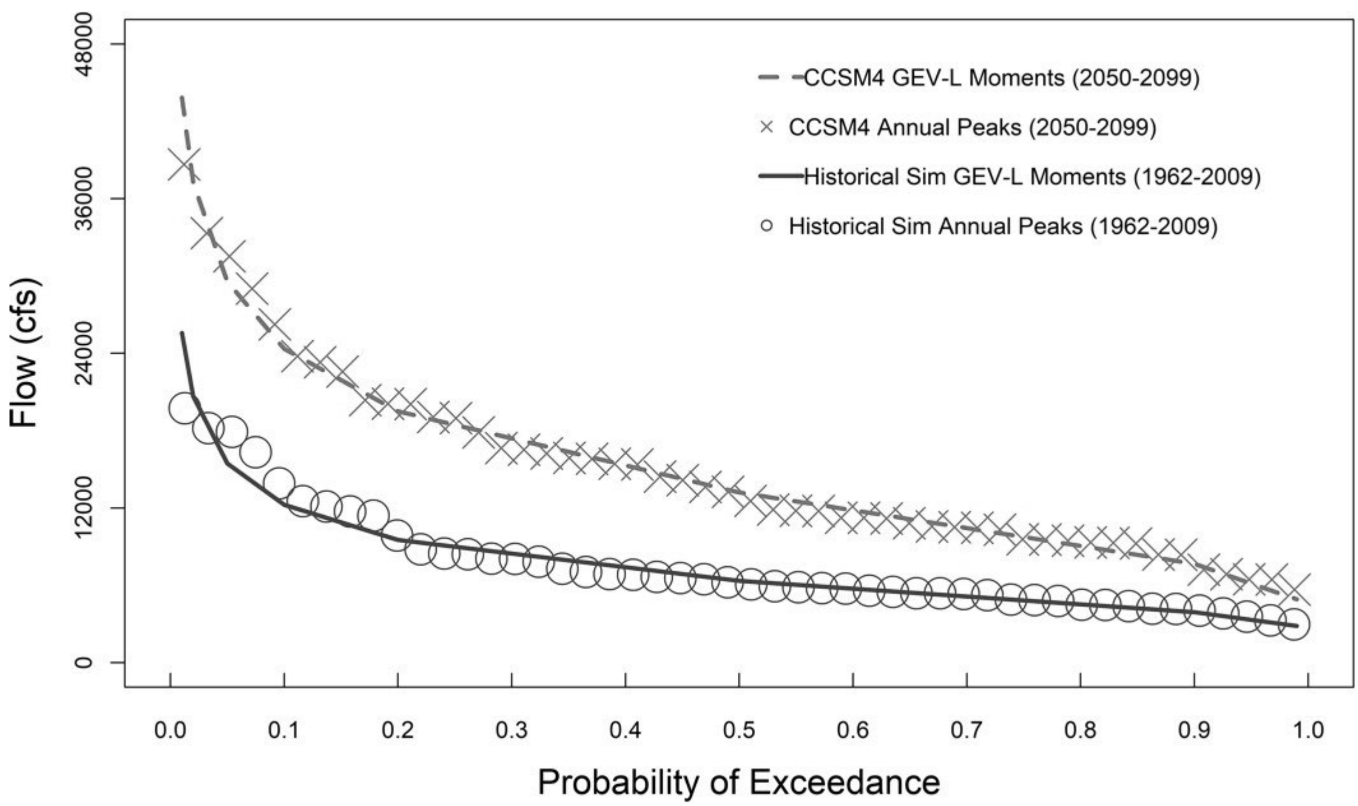


Figure 17 As shown in Figure 14, except for the Newhalem to Marblemount site.

Flood Statistics: Log-Pearson III vs GEV-L Moments

In Figure 18, CDFs of the annual peaks and extreme flood values of two models, CCSM4 and NorESM1-M, were plotted to test the fitness of Log-Pearson III values (used in the SC^2 project) as compared to GEV-L moments (used in this study). Among the 10 GCMs, CCSM4 was chosen because it showed the highest flood projection, and NorESM1-M was chosen because it showed the biggest difference in flood projection between the SC^2 project and this study. For CCSM4, both the GEV-L moments and the Log-Pearson III generally fit well with annual peaks under both RCPs (see Figure 18). The NorESM1-M model showed a steep increase in annual peaks when probability of exceedance was low (low return frequency), and floods estimated by the Log-Pearson III were significantly lower than their annual peaks when a probability of exceedance was less than 0.15 (see Figure 18).

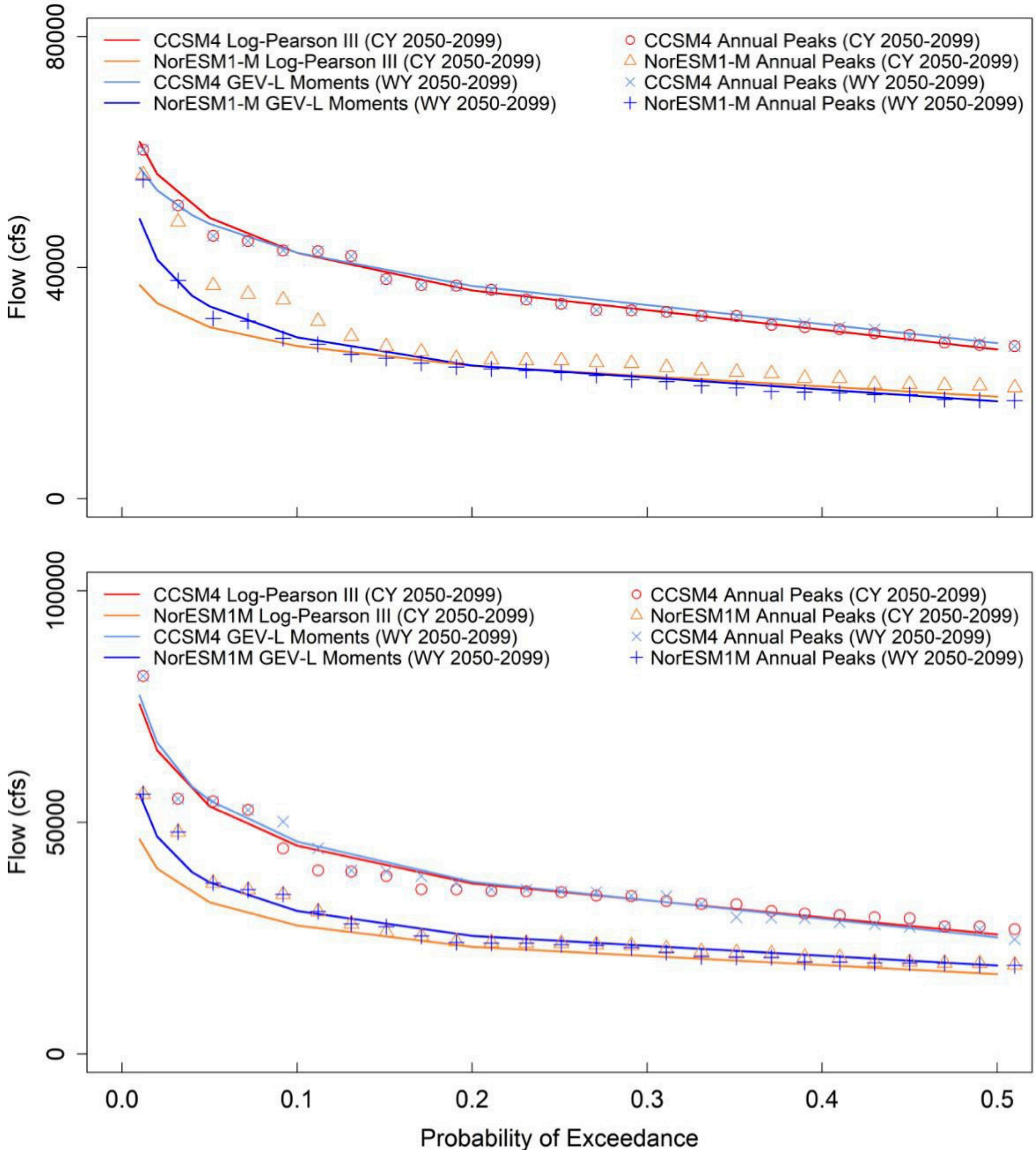


Figure 18 CDFs of annual peaks and respective extreme floods for CCSM4 and NorESM1-M under RCPs 4.5 (top) and 8.5 (bottom) for Ross Dam. Note that annual peaks based on calendar years (CY) and Log-Pearson III values are from the original SC^2 data, while annual peaks based on water years and GEV-L moment values are from this study.

Reporting Percent Change Results

As will be explained further in the Discussion and Conclusion section, the errors in the SC² project that we discovered so far partially contributed to the projected low floods for high return years, but these errors were not grand enough to explain the reported low flood projections in the SC² study. Thus, this study checked flood projections using non-bias-corrected flows, though it was previously assumed that the percent changes in the SC² website were based on bias-corrected flows (see Tables 7-8).

The 100-year floods using non-bias-corrected and bias-corrected flows from the SC² project showed that the values reported on the SC² website came from non-bias-corrected data instead of bias-corrected data (see Table 9). Using the 100-year floods for Ross Dam as an example, it can be assumed that all percent change values on the SC² website are based on non-bias-corrected data.

Table 7 Comparing 100-year flood values and percent changes for non-bias-corrected and bias-corrected data from SC² for Ross Dam under RCP 4.5.

GCM	**100-yr Floods Using Non-Bias-Corrected Flows**			**100-yr Floods Using Bias-Corrected Flows**		
	Historical(CY 1961-2010, cfs)	Future (CY 2050-2099, cfs)	Change (%) from Historical	Historical(CY 1961-2010, cfs)	Future (CY 2050-2099, cfs)	Change (%) from Historical
bcc-csm1-1-m	48,685	38,009	-22%	39,354	30,684	-22%
CanESM2	48,843	38,471	-21%	39,354	31,559	-20%
CSIRO-Mk-3-6-0	48,753	53,879	11%	39,354	58,816	49%
CCSM4	48,445	40,616	-16%	74,746	61,753	-17%
CNRM-CM5	48,541	44,039	-9%	39,354	35,049	-11%
HadGEM2-CC365	48,860	44,825	-8%	39,354	37,986	-3%
HadGEM2-ES365	48,887	60,300	23%	39,354	54,751	39%
IPSL-CM5-MR	48,633	60,322	24%	39,354	56,363	43%
MIROC5	48,762	41,143	-16%	39,354	47,679	21%
NorESM1-M	48,797	38,174	-22%	39,354	36,972	-6%

Table 8 As shown in Table 7, except under RCP 8.5.

GCM	100-yrFloods Using Non- Bias-Corrected Flows			100-year Floods Using Bias-Corrected Flows		
	Historical (CY 1961-2010, cfs)	Future (CY 2050-2099, cfs)	Change (%) from Historical	Historical(CY 1961-2010, cfs)	Future (CY 2050-2099, cfs)	Change (%) from Historical
bcc-csm1-1-m	48,448	61,289	27%	39,354	50,186	28%
CanESM2	48,671	43,613	-10%	39,354	44,382	13%
CSIRO-Mk-3-6-0	48,523	56,736	17%	39,354	48,547	23%
CCSM4	48,646	51,052	5%	74,436	75,529	1%
CNRM-CM5	48,922	38,278	-22%	39,354	32,658	-17%
HadGEM2-CC365	48,465	62,629	29%	39,354	58,122	48%
HadGEM2-ES365	48,825	49,419	1%	39,354	60,417	54%
IPSL-CM5-MR	49,674	55,718	12%	39,354	50,884	29%
MIROC5	48,561	43,858	-10%	39,354	53,586	36%
NorESM1-M	48,890	43,023	-12%	39,354	46,337	18%

Table 9 Percent change statistics for Ross Dam as calculated from Tables 11 and 12 and asreported on the SC^2 website.

	RCP 4.5			RCP 8.5		
	Non-Bias-Corrected	**Bias-Corrected**	**SC^2 Reported**	**Non-Bias - Corrected**	**Bias-Corrected**	**SC^2 Reported**
Min	-22%	-22%	-22%	-22%	-17%	-22%
Mean	-6%	7%	-6%	4%	23%	4%
Max	24%	49%	24%	29%	54%	29%

Changes in Peak Flow Timing

All models produced earlier dates for the average annual peak flow for the three time periods (2000-2049, 2025-2074, and 2050-2099) under both RCPs 4.5 and 8.5 as compared to the historical simulation dates from 1962-2005 (see Figures 19-20 and J1-M6), except for CNRM-CM5 under RCP 8.5 for Ross Dam where the peak flow dates for the 2000-2049 time period were the same for historical simulation and the model (see Figure J4). Additionally, all models produced increasingly earlier dates as the time periods increased, and models under RCP 8.5 produced earlier dates than models under RCP 4.5. For example, the bcc-csm-1-1-m model, one of the 10 GCMs, under RCP 4.5 for Ross Dam produced an average annual peak date of April 13th for the 2000-2049 time period, March 13th for the 2025-2074 time period, and February 2nd for the 2050-2099 time period as compared to the historical simulation date of April 25th (see Figure 19). Under RCP 8.5, the bcc-csm-1-1-m model produced an average annual peak date of April 12th, March 4th, and January 12th for the time periods of 2000-2049, 2025-2074, and 2050-2099, respectively (see Figure 20).

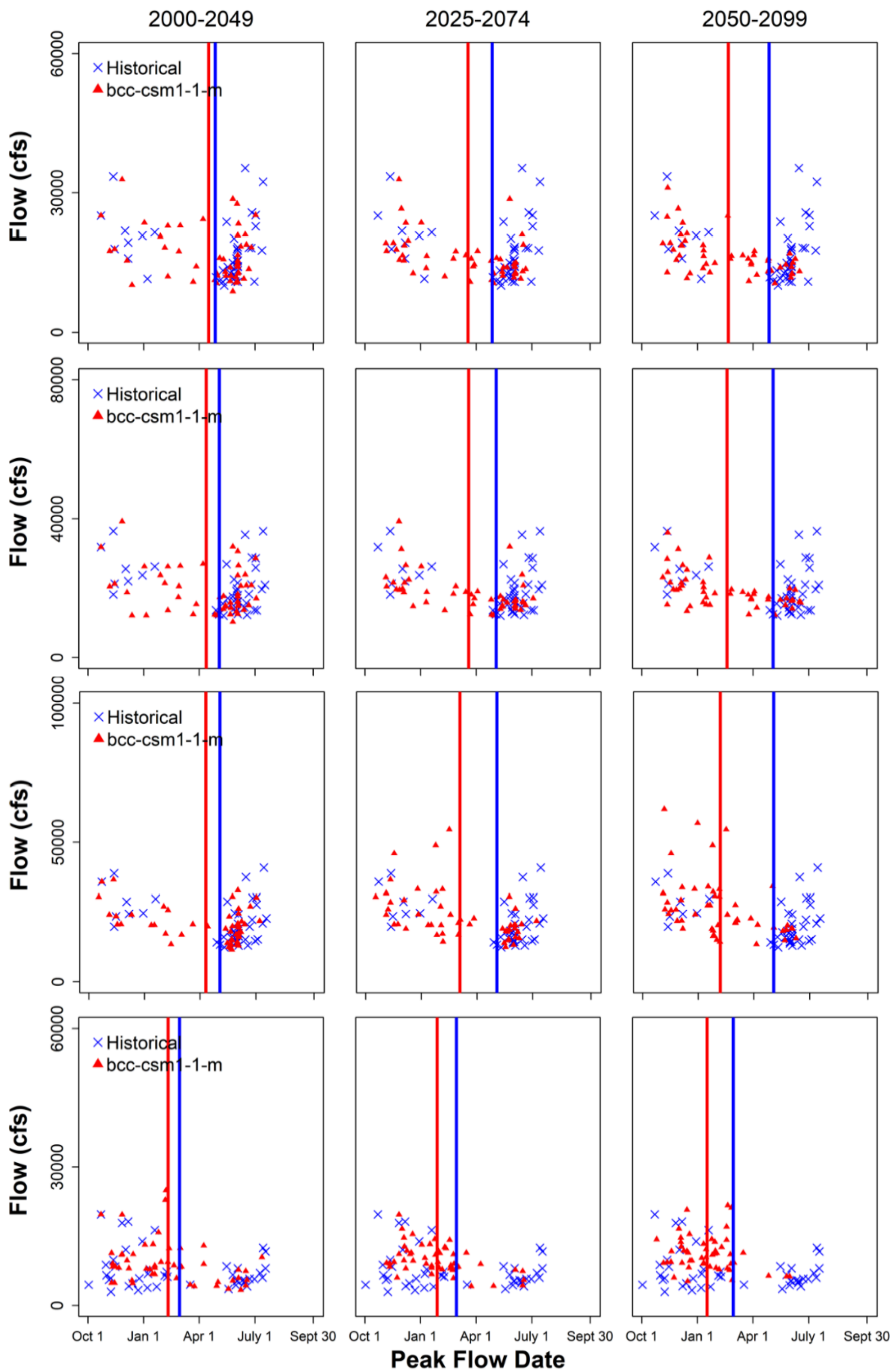


Figure 19 The flow magnitude and occurrence dates of annual peak flows during 2000-2049, 2025-2074, and 2050-2099 from the bcc-csm1-1-m model as compared to the historical simulation from 1962-2005 for Ross Dam (top), Diablo Dam (second), Gorge Dam (third), and the Newhalem to Marblemount site (bottom) under RCP 4.5. The blue and red lines indicate the mean peak flow occurrence date for the historical and future simulations, respectively.

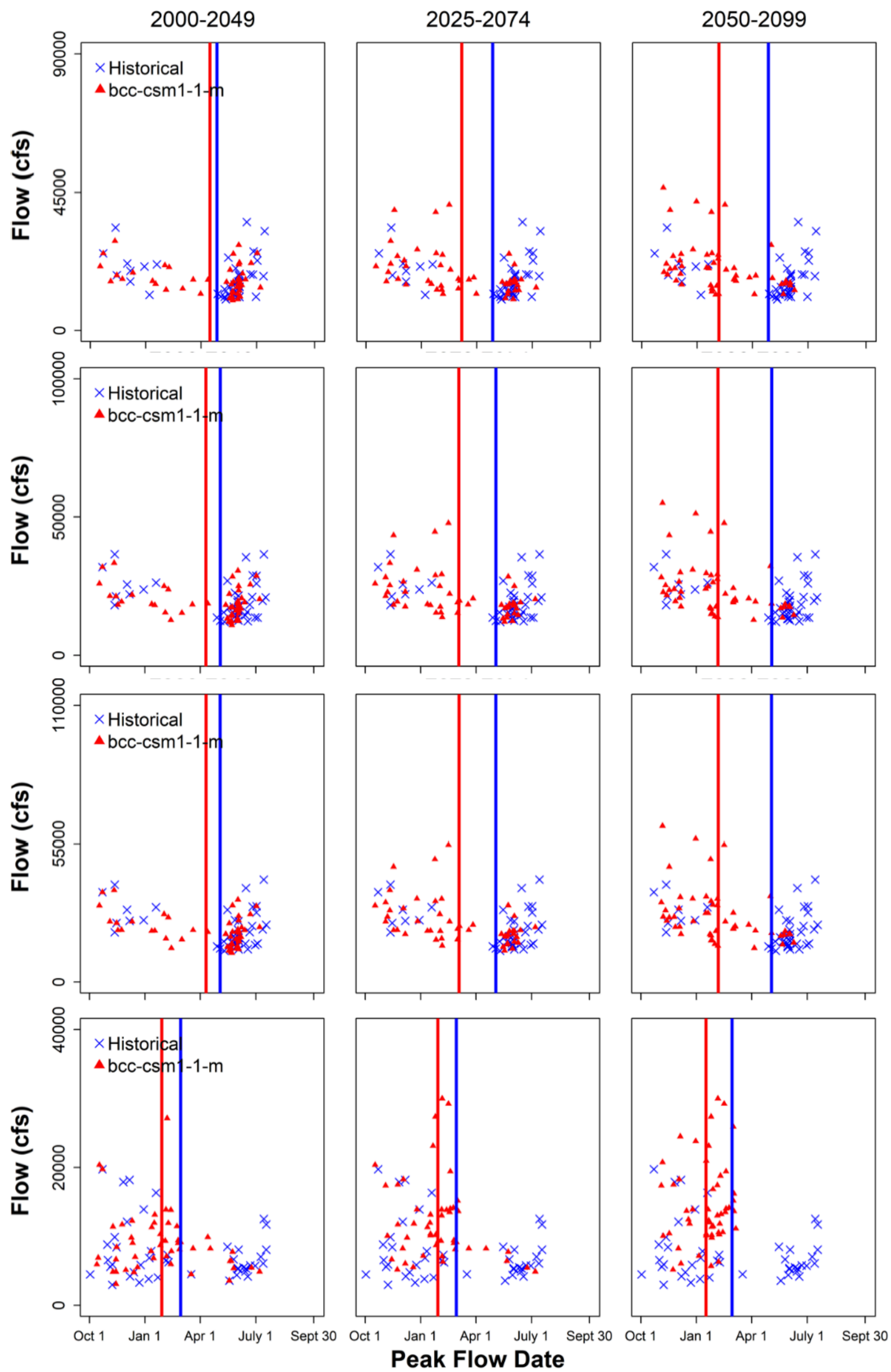


Figure 20 As shown in Figure 19, except under RCP 8.5.

Discussion and Conclusion

The SC^2 project shows that climate change will decrease flood risks for low-frequency floods such as 50- and 100-year floods for three dams in the Upper Skagit River, which is inconsistent with previous studies (Hamlet et al., 2013; Lee et al., 2016; Hamman et al., 2016). Thus, this study revisited results from the SC^2 project to identify the causes of inconsistency. While revisiting data and results from the SC^2 project, this study noticed the following potential problems:

- Calendar years were used to extract annual peak flows rather than water years. While they may use calendar years because this measure is easier to explain to the public, since the form of cool season (Oct-Mar) precipitation (e.g., precipitation falling as rain versus snow) influences the following spring and summer streamflow in the Skagit River basin, water years (Oct-Sept) should be used to evaluate how the changes in the form of cool season precipitation directly affect the following spring/summer flows, as is common with most hydrology research.
- A historical time period of 1962-2009 was used. Since all GCMs produce historical simulation data up to 2005 and project future climate conditions under different RCPs from 2006, it would be more reasonable to remove 2006-2009 from the historical period and consider this part of the future flow time-series. Time-series of annual peaks for the Ross Dam also show that a historical period of 1983-2005 better reproduces the historical observed data than a historical period of 1983-2009 (R^2 = 0.55 and 0.50, respectively; see Figures 2 and 3). There was no significant difference between the two historical periods for the percent change results and major flood trends. By using a historical period of 1962-2005, this study found smaller maximum percent change values as compared to the results from 1962-2009 (see Tables 3-6).
- As the CCSM4 model is the only outlier in the historical simulations from all GCMs, and Bandaragoda et al. (2015) and Bandaragoda et al. (2019) used one historical simulation to validate their results, one historical simulation that comes from any model except for CCSM4 should be used as the historical simulated dataset. Since the historical CCSM4 data showed higher flows for low-frequency floods (probability of exceedance < 0.2, see Figures 2 and 3), removing the historical CCSM4 data resulted in increased flood risks for low-frequency floods, which are closer to the expected results of this study.
- The White Chuck and Sauk River above White Chuck sites are incorrectly bias-corrected on the SC^2 website. There are two possibilities for how this happened. First, streamflow at the Sauk River above White Chuck was correctly bias-corrected with the USGS data at the same location, but it was incorrectly noted in the SC^2 website as the White Chuck site. Secondly, streamflow at White Chick site was incorrectly bias-corrected with USGS

data from the Sauk River above White Chuck. Based on the available data, this study cannot confirm which is the source of error.

- While it is unclear on the SC^2 website if percent changes for the extreme floods are based on bias-corrected or non-bias-corrected data, this study found that the percent changes reported are based on non-bias-corrected data (see Table 9), even for sites that have bias-corrected data available. The use of non-bias-corrected data to calculate percent change flood statistics as reported on the SC^2 website was the main cause of why the flood statistics on the SC^2 website were inconsistent with previous studies. Thus, this study suggests either 1) providing percent changes based on bias-corrected data only, 2) providing percent change data for all sites, but clearly noting which flows are used (i.e., bias-corrected or non-bias-corrected flows), or 3) providing percent change data for non-bias-corrected flows in the form of normalized hydrographs (see Future Considerations section).
- Under both RCPs, the GEV-L moments fit their respective annual peak data more closely than the Log-Pearson III values fit their annual peak data, especially when there is a steep increase in annual peaks (see Figure 18). The GEV-L moments method is recommended to calculate the extreme flood values as opposed to the Log-Pearson Type III method for more accurate results.

The DHSVM model reproduced observed CDFs and time-series of annual peak flows well when annual peak flows were extracted based on water years (see Figures 2-5), validating the use of the model for the creation of the original SC^2 dataset. CDFs of annual peak flows for three future time periods (2000-2049, 2025-2074, and 2050-2099) under two RCPs had similar or higher peak flows than the historical simulation (see Figures 6-7).

By recalculating the flood statistics for various return frequencies, the percent changes of floods estimated from this study also show that flood risks will increase for both high and low-frequency floods (see Tables 3-10; Figures 10-13; Figures B1-I5), which is consistent with results from previous studies (Hamlet et al., 2013; Lee et al., 2016; Hamman et al., 2016). Higher flood risks were projected partially due to the removal of the CCSM4 model data in the historical simulation data. However, removing the historical CCSM4 data is not the only reason why higher flood risks were projected in this study, since there are other GCMs that showed higher percent changes in floods in this study in comparison to the SC^2 study. For example, some GCMs produced percent change values larger than 34%, which was the maximum percent change value for 100-year flood in the SC^2 study for Ross Dam. Other possible contributions of higher flood estimation in this study include the use of water years instead of calendar years and the use of GEV-L moment methods instead of the Log-Pearson Type III distributions. While Log-Pearson Type III distributions are the standard recommendation for use by U.S. federal agencies to conduct flood frequency analyses, this study confirmed that GEV-L moments better fit with CDFs of annual peaks than Log-Pearson III, especially when there is a sharp increase in annual peaks, signifying that GEV-L moments methods are appropriate to estimate low-frequency floods (see Figures 14-18).

An increasing trend of high flows is found when using 50-year averages of annual peaks for the three time periods, especially for RCP 8.5 (see Figures 8-9 and A1-A6). In relation to peak flow timing, this study showed consistent results with previous studies (Lee et al., 2016), in that peaks are projected to occur earlier as time continues throughout the 21st century (see Figures 18-19 and J1-M6). As the Ross, Diablo, and Gorge Dams, as well as the Newhalem to Marblemount site, are all currently snow-dominated, climate change is expected to shift the timing of their annual peak flows since warming will cause more cool season precipitation to fall as rain rather than snow (Lee & Hamlet, 2011). This results in less snow accumulation and stored snowpack, and therefore less flow from snowmelt later in the season. Instead, annual peak flows will follow the seasonal maximum rainfall, resulting in a single larger peak than if precipitation fell as snow. This is consistent with our findings in Figures 18-19 and J1-M6, as this study found the occurrence of future projected annual peak flows during mid-winter through the early spring seasons, which occur earlier than those in the historical record. Additionally, these findings highlight the importance of educated dam management for the purpose of future flood control in the Skagit River basin, as both low and high-frequency floods are expected to occur earlier in the season and increase in flow.

As the percent change results under RCP 8.5 were generally projected to be positive and larger in magnitude (i.e., increased magnitude of floods) than those under RCP 4.5 for all time periods (see Tables 3-6), it is reasonable to say that reducing greenhouse gas emissions reduces future extreme flood risks.

Future Considerations

As the intended audience of the SC^2 website is the interested public, including residents and Native tribes within the Skagit River basin, this study has further considerations on data visualization for the most effective and intelligible scientific communication.

As shown in the percent change data (see Tables 3-6), there are several high maximum percent change values. Thus, it's better to provide median values in addition to mean values in order to properly consider these higher values, which are less influential when solely using median values as currently presented on the SC^2 website.

For sites that lack bias-corrected flows, no hydrograph of average monthly streamflow is available on the SC^2 website. Instead, only a hydrograph of monthly percent changes is seen, which might cause some confusion in understanding the climate change impacts on hydrology. Thus, this study recommends using a normalized flow hydrograph, as shown below, for non-bias-corrected sites, comparing the historical monthly average streamflows with future monthly average streamflows for a selected time period (see Figure 21). These figures would provide the audience with a visual understanding of how climate change will affect both flow magnitude and timing of monthly streamflows, without presenting the actual non-bias-corrected streamflow data, which may be ill-advised to present before knowing the full importance of bias-correction in this project (see the methods section for more about the process of normalization). Additionally, it may be helpful to include a hydrograph of the average historical observation so the audience can compare the historical observed data with the modeled historical data.

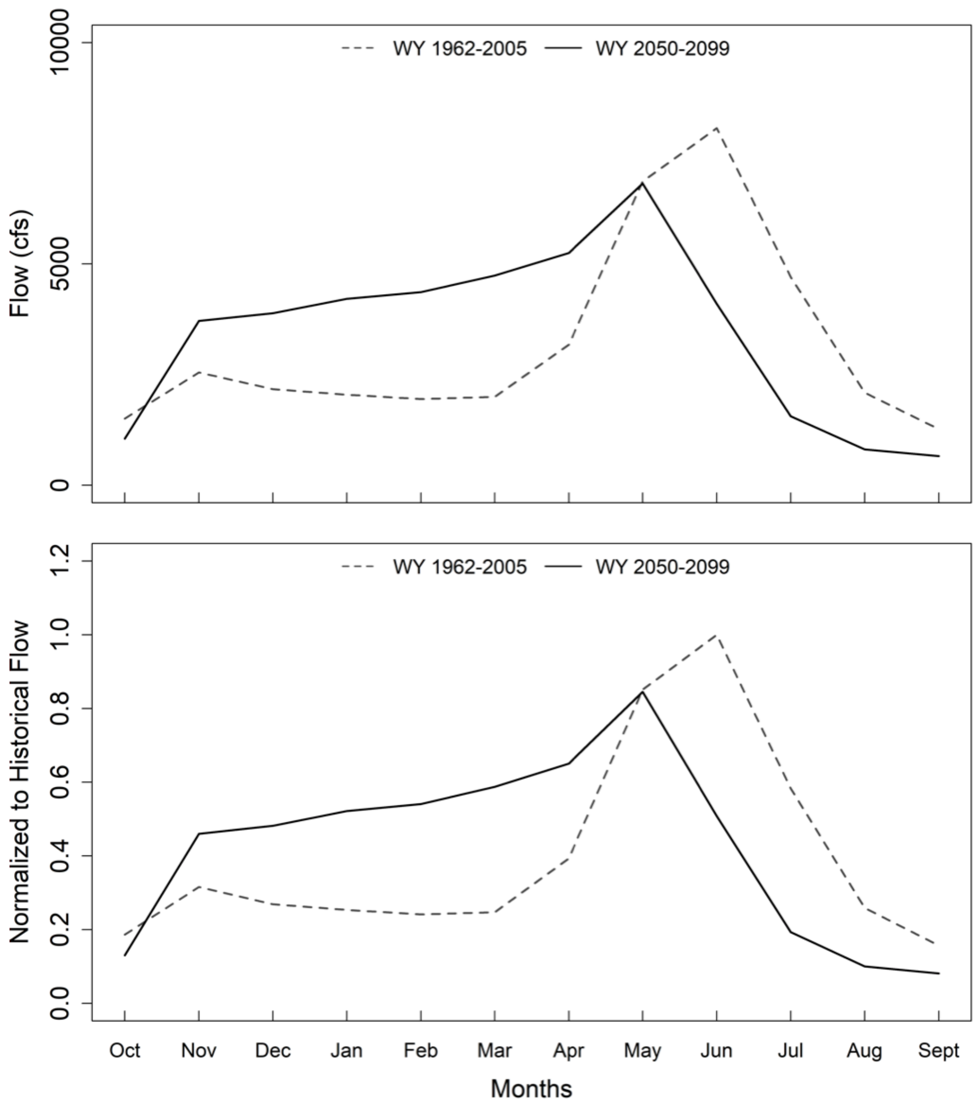


Figure 21 The hydrograph of average monthly streamflow (top) and normalized monthly hydrograph (bottom) for Ross Dam under RCP 4.5.

In the monthly streamflow section of the SC² website, the legends for historical average monthly flows show years for the future time periods, even though it is the historical simulation. For example, the legend of a monthly streamflow plot on the SC² website reads "Historical Average climate model projects Mean Jun streamflow…for the period 2038 to 2067" when the selected *future* time period was 2038-2067 (Skagit Climate Science Consortium, 2015). This legend wording is confusing to the audience and should be corrected to the proper historical time period of 1962-2009 (e.g., Historical Average climate model projects Mean Jun streamflow […] for the period 1962 to 2009).

Next Steps

Further research should investigate the statistical significance of percent changes in future projected data (e.g., "What is the magnitude and what are potential impacts of a +2% change in the 100-yr flood?"). To further understand the importance of bias correction on projected streamflow data, peak flow timing and monthly averages of non-bias-corrected data should be compared to those from bias-corrected data to highlight the impacts of bias correction.

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