Climatic Change (2008) 87:451–469
DOI 10.1007/s10584-007-9306-8

Impact of climate change on Pacific Northwest hydropower

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Received: 31 August 2005 / Accepted: 10 May 2007 / Published online: 25 July 2007

Abstract The Pacific Northwest (PNW) hydropower resource, central to the region's electricity supply, is vulnerable to the impacts of climate change. The Northwest Power and Conservation Council (NWPCC), an interstate compact agency, has conducted long term planning for the PNW electricity supply for its 2005 Power Plan. In formulating its power portfolio recommendation, the NWPCC explored uncertainty in variables that affect the availability and cost of electricity over the next 20 years. The NWPCC conducted an initial assessment of potential impacts of climate change on the hydropower system, but these results are not incorporated in the risk model upon which the 2005 Plan recommendations are based. To assist in bringing climate information into the planning process, we present an assessment of uncertainty in future PNW hydropower generation potential based on a comprehensive set of climate models and greenhouse gas emissions pathways. We find that the prognosis for PNW hydropower supply under climate change is worse than anticipated by the NWPCC's assessment. Differences between the predictions of individual climate models are found to contribute more to overall uncertainty than do divergent emissions pathways. Uncertainty in predictions of precipitation change appears to be more important with respect to impact on PNW hydropower than uncertainty in predictions of temperature change. We also find that a simple regression model captures nearly all of the response of a sequence of complex numerical models to large scale changes in climate. This result offers the possibility of streamlining both top-down impact assessment and bottom-up adaptation planning for PNW water and energy resources.

1 Introduction

Thanks to its large hydroelectric resource, the Pacific Northwest (PNW) has long benefited from plentiful, inexpensive electricity (Tollefson 1987). The hydroelectric dams of the Columbia River Basin (CRB) currently account for about two-thirds of the total installed generation capacity in the PNW and, in an average water year, supply about three-quarters

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of the region's electricity (Northwest Power and Conservation Council 2005). There are over 100 hydroelectric projects in the CRB, with federally owned dams making up more than half of the total installed generating capacity.

The PNW Electric Power Planning Act of 1980 mandated that the federal dams in the CRB be managed not only to provide inexpensive power, but also to protect fish and wildlife. The Endangered Species Act listing of Snake River sockeye in 1991, as well as the other listings that followed, have ensured that fish and wildlife protection will continue to be a significant factor in how the hydroelectric resource is managed in the years and decades to come. The dams of the CRB are further expected to provide flood control and recreation services, and the water itself is also claimed for irrigation and municipal use. These many demands on the system are often in conflict, particularly as the total supply of water is limited (Callahan et al. 1999; Cohen et al. 2000).

Compared to other large river systems, the ratio of storage to annual flow is low in the CRB. Total storage capacity in the CRB is only about 30% of annual flow at The Dalles (Bonneville Power Administration 2001). The man-made water storage that does exist in the CRB is complemented by natural water storage in the form of mountain snowpack. Snowmelt in the spring and early summer, plus water stored in dam reservoirs, usually provides enough streamflow to allow hydroelectric production throughout the otherwise dry summer, until the rains begin in October.

This system is vulnerable to natural patterns of climate variability (Miles et al. 2000) and to anthropogenic climate change. With the temperature increases expected as a result of climate change, more precipitation will fall as rain instead of snow, and the spring melt will come earlier (Mote et al. 2003). This, coupled with a possible climate change-driven decrease in total annual precipitation, could reduce hydroelectric generation potential substantially, and significantly impact flows for fish and other interests in the CRB.

Created by the PNW Electric Power Planning Act of 1980 (the Act), the Northwest Power and Conservation Council (NWPCC) is a compact agency of the four Northwest US states (Oregon, Washington, Idaho, and Montana). Its mission is to coordinate power planning and conservation of fish and wildlife resources for the region. As mandated by the Act, the NWPCC must prepare and adopt a "20-year electric power plan that will guarantee adequate and reliable energy at the lowest economic and environmental cost to the Northwest," and review that plan at least every 5 years.

In May of 2005, the Council released the fifth power plan in its history (Northwest Power and Conservation Council 2005; referred to hereafter as the 5th Power Plan). The 5th Power Plan proposes that the region's predicted demand growth over the next two decades be met with a combination of additional conservation, wind power, and thermal generation. By 2025, electricity demand is expected to grow by about 5 average gigawatts (aGW), though the full range of forecasts for possible demand growth allows that demand may increase up to three times that much, or stay at current levels (Northwest Power and Conservation Council 2005, Appendix A, "Demand Forecast").

In order to find the most robust portfolio of generating resources, the Council developed a model (referred to here as the Portfolio Model) to evaluate a large number of possible portfolios against a range of possible futures. The Portfolio Model considers (via Monte Carlo simulation) uncertainty in a wide array of variables that are important to regional power planning—including natural gas prices, renewable energy incentives, industrial and residential electricity demand, forced outages of generation facilities, and taxes on carbon dioxide emissions (Northwest Power and Conservation Council 2005, Chapter 6, "Risk Assessment & Management").

Though federal regulation of greenhouse gas emissions is considered in the Council's analysis, the impact of climate change on the availability of hydropower generation is not.

However, climate change is relevant within the 20-year planning horizon and, arguably, we are better equipped to make predictions about the climate system than about the political process that will determine the future regulation of greenhouse gas emissions or renewable energy production incentives. Appendix N of the 5th Power Plan (Northwest Power and Conservation Council 2005, Appendix N, "Effects of Climate Change on the Hydroelectric System"; hereafter Appendix N) contains an initial impact analysis, and recognizes that climate change may have a significant impact on PNW hydropower. Indeed, the Council is interested in including the impacts of climate change in the Portfolio Model and thus in its decision process (Fazio, personal communication), but understandably has not been able to do so, owing mainly to a limited capability to analyze general circulation model (GCM) outputs and conduct hydrologic modeling.

The present work is designed to fill this gap by conducting a comprehensive review of the latest GCM outputs available from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center (DDC). Other work on water resources impacts of climate change in the CRB has included multiple models (Snover et al. 2003) or multiple emissions scenarios (Payne et al. 2004), while the present research aims to capture as large a range of climate predictions as possible. Our study includes roughly the same set of GCMs as Mote et al. (2003), but more recent simulations covering a wider range of emissions scenarios are used. The climate scenario data presented in this work may also be useful for other PNW impact studies.

2 Approach

If regional adaptation strategies are to be effective in preparing for the impacts of climate change, many decisions will need to be made without waiting for the uncertainty in climate predictions to be reduced. Robust regional climate adaptation strategies can be developed in the face of uncertain climate predictions, but an estimate of the range of possible climate futures is necessary. Accordingly, logical first steps in managing uncertainty in a regional impact assessment would be to attempt to quantify the overall uncertainty, identify the key contributors to uncertainty, and evaluate the extent to which uncertainty is a barrier to decision making.

In accordance with the NWPPC's risk management framework for energy planning, a risk assessment approach (Dessai et al. 2005; Jones 2001) is appropriate in planning for the impacts of climate change. In order to include information about climate change in its risk management process using the Portfolio Model, a probability density function (PDF) of the potential impacts will be necessary. This is in contrast to many other adaptation planning situations, where a probabilistic expression of the potential impacts of climate change on a region is at best difficult to incorporate in the decision making process and at worst irrelevant to any decision on the horizon (Dessai and Hulme 2004). While only a simple PDF is presented here, we lay useful groundwork for further development of this approach by bounding the range of potential impacts, exploring the sources of uncertainty in these predictions, and demonstrating the significance of these impacts to regional power planning.

To explore the range of possible climate change impacts on the PNW hydropower system, a series of modeling and analytic steps are chained in an end to end analysis (see Fig. 1). First, temperature and precipitation predictions for the 21st century under different emissions scenarios are collected from the set of leading GCMs. These gridded global predictions are then interpolated to the area of interest, the CRB, to produce a set of regional climate perturbations. Next, the perturbations are applied to high resolution historical climate data, producing a detailed time series suitable for input to a macroscale hydrologic model. This model is used to simulate streamflows under the perturbed climate.

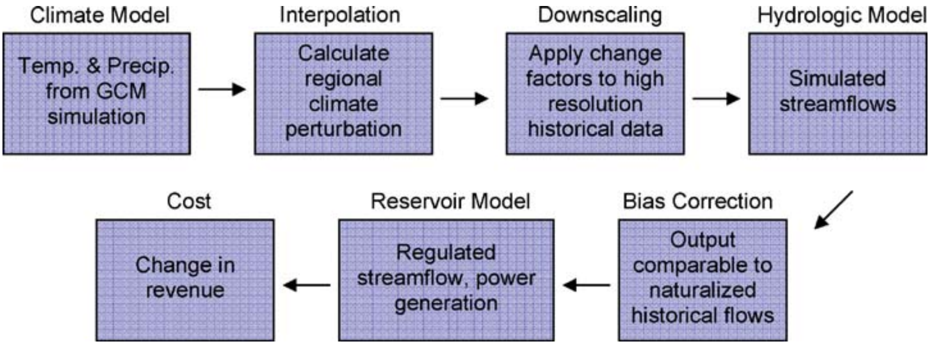

Fig. 1 Overview of modeling and data processing steps, after Hamlet and Lettenmaier (1999) and Lettenmaier (2004)

A bias correction procedure is then employed to remove modeling errors, making these streamflow predictions more directly comparable to observed streamflows. Moving beyond previous treatments we next run the corrected flows through two different reservoir models in parallel to simulate dam operations, and power generation. Finally, electricity price forecasts are applied to estimate revenue from hydroelectric generation, and calculate the change in revenue relative to non-perturbed operations.

2.1 Climate models and emissions scenarios

Seven major climate modeling groups contributed simulations forced by different emissions pathways from the Special Report on Emissions Scenarios (Intergovernmental Panel on Climate Change 2000) for the IPCC's Third Assessment report (IPCC 2001). Monthly temperature and precipitation data for each of the GCM/scenario pairings indicated in Table 1 were collected from the IPCC DDC for use in the present analysis.

2.2 Interpolating and downscaling GCM outputs

To generate the suite of climate scenarios used to drive the remainder of the present impact analysis, the GCM outputs from the DDC are interpolated to a 0.125 degree grid representing the CRB. In this study we apply the delta method, also known as the change factor method (Wilby et al. 2004). This method requires change factors (additive for temperature and multiplicative for precipitation) of simulated historical climate and future climate. Averaging over the CRB, monthly mean temperature and precipitation change factors from 1961–1990 are calculated for the following periods: 2010–2039, 2040–2069, and 2070–2099.

Table 1 GCM simulations available from the DDC

GCM/emissions scenario	A1B	A1T	A1FI	A2	B1	B2
CCSR/NIES	✓	✓	✓	✓	✓	✓
CGCM2				✓		✓
CSIRO-Mk2	✓			✓	✓	✓
ECHAM4				✓		✓
GFDL-R30				✓		✓
HadCM3			✓	✓	✓	✓
NCAR-PCM				✓		✓

Downscaling is achieved by applying these change factors, or perturbations, to high resolution (0.125 degree spatial resolution, with a daily time step) historical data covering the period 1915–2003. This produces a set of historical records adjusted for climate change perturbations for 2010–2039, 2040–2069, and 2070–2099 (hereafter, the 2020s, 2050s, and 2080s, respectively). Using the delta method to produce climate scenarios is advantageous because a climate change modulated version of the historic record is relatively easy for water resources managers to interpret and incorporate in existing planning processes (Snover et al. 2003).

In calculating change factors, this study uses 30-year extracts of GCM data, which is longer than previous applications of the delta method approach in the CRB (e.g., Snover et al. 2003). Given that the downscaling method assumes complete reliance on the historical record to provide variability, taking a longer average from the GCM output is preferable [IPCC Task Group on Scenarios for Climate Impacts Assesment (IPCC-TGCIA) 1999].

2.3 Modeling of CRB hydrology

The impacts of these climate scenarios on surface water flows in the CRB are evaluated using the variable infiltration capacity (VIC) hydrologic model (Liang et al. 1994). The VIC model estimates total water flux and snowpack based on climatic data, soil types, and other parameters. For this study, VIC is run at 0.125 degree resolution, with a daily timestep. Streamflows at key drainage points in the CRB are then calculated by a river routing model (Lohmann et al. 1998) based on the fluxes produced by VIC and CRB topology. Selection of drainage points is determined by requirements of the reservoir models, introduced below. Simulated flows are unregulated (i.e., without dams or withdrawals), and thus only comparable to 'naturalized' observed flows. Next, a bias correction procedure is applied (Hamlet et al. 2003; Snover et al. 2003) to correct the simulated flows to more closely resemble streamflow distributions seen in naturalized observations.

From the more than 70 climate scenarios shown in Fig. 2, 35 were chosen for modeling in this study (see Table 2). Climate scenarios were selected to ensure that the scenarios resulting in the highest and lowest predicted flow (i.e., the warmest and driest conditions, and the coolest and wettest conditions, respectively) were included.

As discussed in Sect. 3, CCSR/NIES A1FI and CSIRO-Mk2 B1 are identified as the 'high' and 'low' scenarios. These two scenarios represent the best and worst cases in terms of hydroelectric generation as predicted by the modeling chain employed here. Impact analysis of these scenarios helps provide policymakers (particularly the NWPCC) with a more complete picture of the range of possibilities for the costs of climate change. The ECHAM4 scenarios, for the A2 and B2 emission scenarios, were also included in the detailed analysis to provide a more complete picture of the variation within the range staked out by the high and low scenarios, and to allow comparison with the NWPCC's results (Northwest Power and Conservation Council 2005; Appendix N).

Although not every scenario is run through the entire model chain, we are able to estimate the impacts associated with the full set of scenarios via a simple regression model (Jones 2001) that is able to capture virtually all of the variability of the larger, physically based models. The regression model will be discussed in greater detail in Sect. 4.

2.4 Modeling reservoir operations

In order to estimate the potential impacts of a climate scenario, corrected streamflows are run through a reservoir model that considers rules for regulating flows through the system's dams and calculates resulting power generation. Two reservoir models are run: ColSim

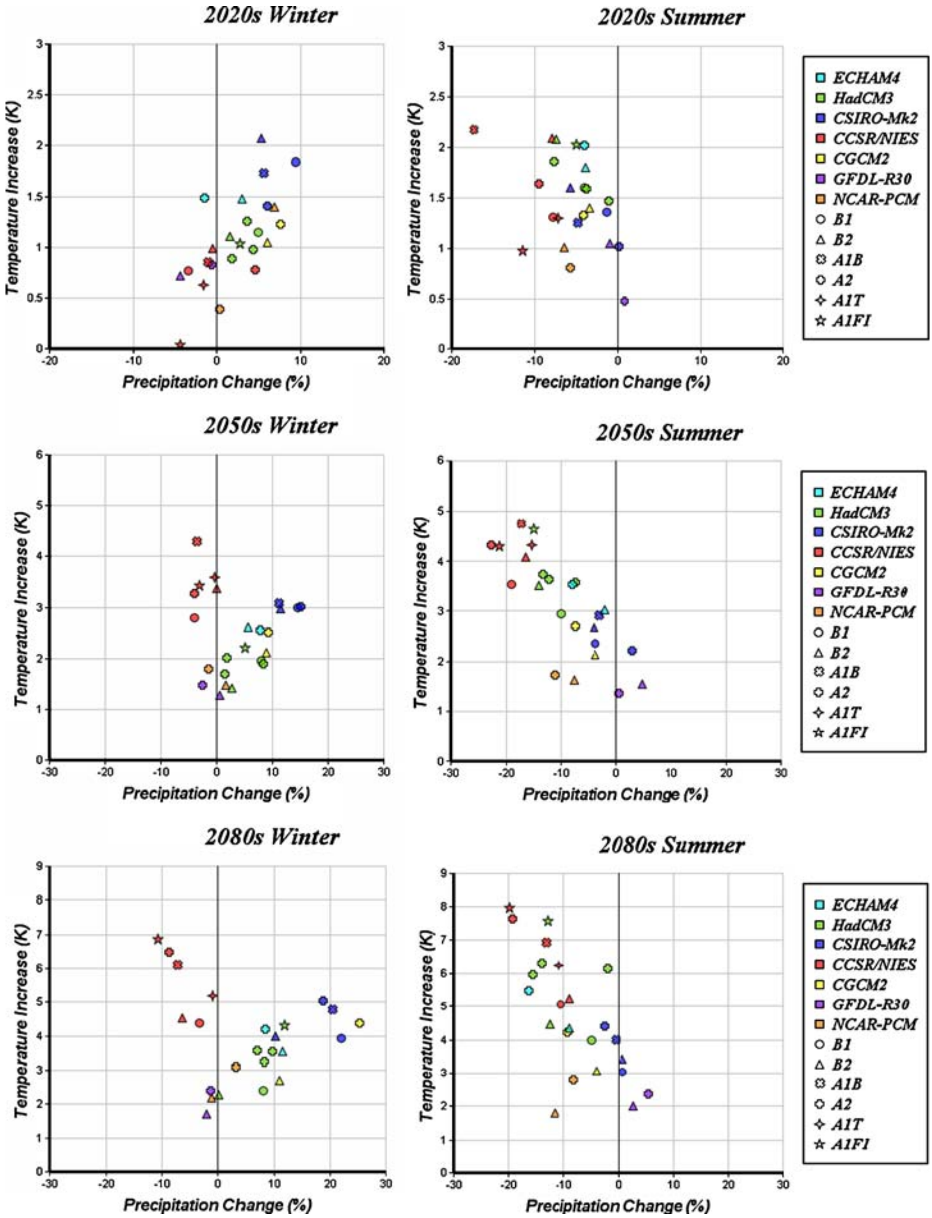

Fig. 2 Perturbations for the CRB. Predicted seasonal departures from the 1961–1990 mean for the 2020s, 2050s, and 2080s. *Shading color* indicates model, while *shape* indicates SRES scenario. Note that the *x* and *y axis* scales are not consistent across the three time periods

(Hamlet and Lettenmaier 1999), which is run on the entire 'perturbed' climate record of 1916–2002, and Genesys (Northwest Power and Conservation Council 2003), which covers a more limited period (1930–1978), but simulates a larger number of generation facilities and is used by the NWPCC.

Table 2 GCM/emissions scenario pairs for which flows have been modeled using VIC

GCM/emissions scenario	A1FI	A2	B1	B2
CCSR/NIES	20/50/80		20/50/80	20/50/80
CSIRO-Mk2	20/50/80		20/50/80	
ECHAM4		20/50/80		20/50/80
GFDL-R30		20/50/80		20/50/80
HadCM3	50/80	20/50/80		50/80

Time periods are abbreviated (e.g., '20' for the 2020s). A 'no perturbation' scenario was also run in addition to the 34 combinations shown here.

Results from either of these operational models must be interpreted cautiously. Both are reasonably accurate in reproducing the effects of specific operational decisions; however, the models themselves do not attempt to optimize the system (e.g., the critical rule curves) to improve performance under the new climatic circumstances. ColSim, in particular, is useful for experimenting with new operating rules, as in Hamlet et al. (2002) and Payne et al. (2004). Therefore, results from these reservoir models may be somewhat pessimistic; however, this effect is expected to be relatively small (Payne et al. 2004). Additionally, it is likely that any optimization of dam operations in response to climatic changes will be slow—given the lack of institutional incentives, and the potential for increased conflict with instream flow requirements for fish and other interests (Callahan et al. 1999). In fact, it is conceivable that hydroelectric generation will not be prioritized over other interests in the future, in contrast with today's operating policy.

2.5 Estimating economic impact of change in hydropower potential

The value of the change in hydroelectric generation can be estimated in a number of ways. One approach is to estimate the sale price of electricity had it been available. Alternatively, the cost of replacement power can be estimated. These two estimation methods may yield significantly different results, given that electricity from federal dam projects is currently sold at cost while replacement power is generally expensive. We simply apply the NWPCC's forecast for 2006 bulk electricity prices (Northwest Power and Conservation Council 2005; Appendix N). Future electricity prices constitute a major source of uncertainty, but we use this approach to allow direct comparison with the NWPCC results.

Uncertainty exists in forecasts of electricity prices because of possible changes to both the supply curve (electricity generation) and demand curve (electricity consumption). As the present study demonstrates, climate change may have a substantial effect on the supply of electricity; however, climate change may also affect demand. Currently, the region's electricity consumption peaks in the winter season, but warmer summertime temperatures are likely to increase electricity demanded to power air conditioning. This may lead to a double-peak in annual electricity demand, and a reduction in electricity available for export to California.

3 Results

3.1 Climate scenarios

Figure 2 shows the predicted seasonal changes in temperature and precipitation for the PNW for all the scenarios examined in this study.

In constructing the input data set for VIC, monthly perturbations for temperature and precipitation are applied to the historical record, as discussed above. Since most of the precipitation in the region falls during the winter, changes in summertime precipitation are less significant. Nonetheless, the trend across all the models is for warmer temperatures in the summer to be associated with lower precipitation. In the wintertime, most of the models exhibit the opposite association, with warmer winters being accompanied by more precipitation—with the notable exception of the CCSR/NIES model (for which higher temperatures tend to be associated with lower precipitation regardless of the season).

Confidence in these predictions generally decreases with greater distance into the future. Also, our confidence tends to be greater in predictions that agree with one another. The CCSR/NIES results, for example, are clearly different from results of other models in winter 2050s and more so in winter 2080s.

3.2 Results of streamflow and power production

The high and low flow scenarios (CCSR/NIES A1FI and CSIRO-Mk2 B1, respectively), plus the ECHAM4 scenarios and baseline 'no perturbation' scenario, are carried through to the reservoir models.

The hydrograph envelope over the modeling period (1916–2002), along with average flow, of corrected streamflows at The Dalles for the high and low flow scenarios in 2020s and 2080s, plus the simulated baseline (or control) flows, are shown in Fig. 3.

Higher predicted temperature and winter precipitation under CSIRO-Mk2 B1 result in increased simulated streamflows December through May. In this same period, higher temperatures coupled with lower precipitation as predicted by CCSR/NIES A1FI results in reduced total flow. Simulated streamflows for June through November are lower than the control for both GCMs, because of earlier melt-off (CSIRO-Mk2 and CCSR/NIES) and reduced precipitation (CCSR/NIES). Average total flows over the whole water year are *higher* for CSIRO-Mk2 B1 (by about 7.2×10^9 and 22.2×10^9 m^3 for 2020s and 2080s, respectively), and *lower* for CCSR/NIES A1FI (by about 28.5×10^9 and 68.1×10^9 m^3 for 2020s and 2080s, respectively). Though their hydrographs are not shown, the ECHAM4 scenarios result in significant decreases in average annual flow, though not as severe as CCSR/NIES A1FI. The 2080s scenarios are included in the above discussion to demonstrate the impact extremes examined in this study. Because of its greater relevance to current planning efforts, 2050s scenarios are discussed in place of the 2080s scenarios in the hydropower discussion below.

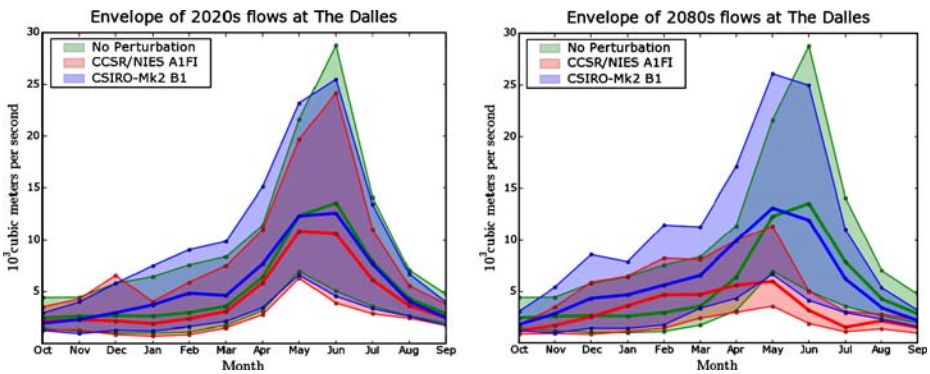

Fig. 3 Hydrograph for the high flow and low flow scenarios for the 2020s and 2080s, compared with the baseline flows, at The Dalles

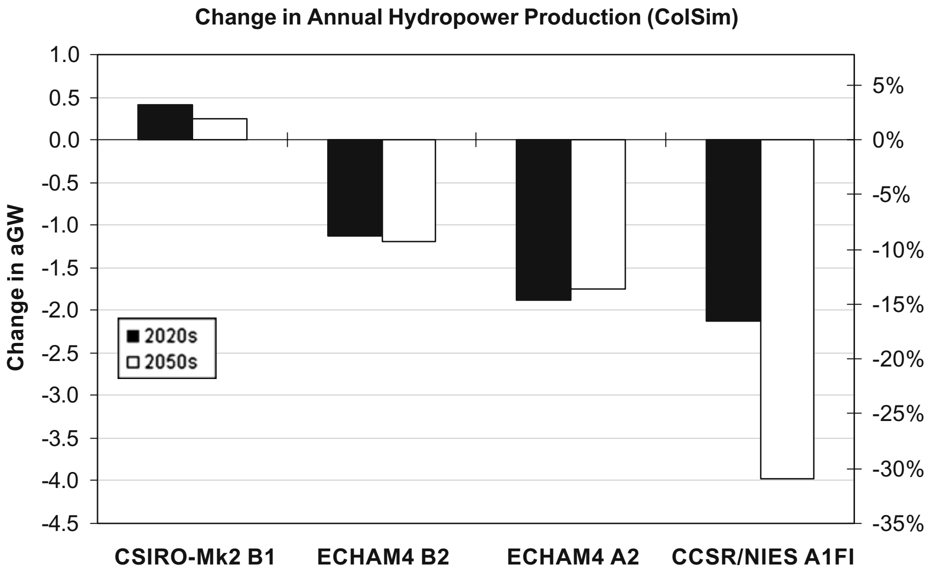

Fig. 4 Change in average annual hydropower production, as simulated by ColSim, in aGW for the 2020s and 2050s. The *right axis* is percent of simulated baseline hydropower production

Similar to the simulated changes in average annual streamflow, CSIRO-Mk2 B1 shows a slight increase in hydro generation from a simulated baseline of more than 13 aGW, while CCSR/NIES A1FI and ECHAM4 scenarios show large decreases (see Fig. 4). However, though a slight increase in *average* hydro potential is predicted for CSIRO-Mk2 B1, the ColSim simulation for CSIRO-Mk2 B1 actually shows a lower minimum value for the worst year under both the 2020s and 2050s scenarios. Since power planning (and other water resources planning) is often based on the worst, or critical, year—the CSIRO-Mk2 B1 scenarios for the 2020s and 2050s still have the potential to represent a reduction in hydropower production compared with the baseline simulation. Also, the ColSim simulation shows that targets for instream fish flows are missed more frequently under *all* scenarios (including CSIRO-Mk2 B1) in the 2020s, 2050s, and 2080s.

To compare the two operational models, changes in hydropower production for the 'high' and 'low' scenarios as predicted by the Genesys reservoir model are shown in Fig. 5 alongside the ColSim results. Because the Genesys model only operates over the years 1930–1978, the ColSim results have been limited to these years for comparison. The two reservoir models make similar predictions in the baseline case and for the relatively mild CSIRO-Mk2 B2 scenarios, but ColSim shows a noticeably more severe effect resulting from the larger CCSR/NIES A1FI scenario than does Genesys.

In comparison with the results in the NWPCC's Appendix N, this work presents a less optimistic view of the potential effect of climate change on PNW hydropower. Appendix N analyzes the impacts of perturbations predicted by HadCM2 and ECHAM4. The ECHAM4 results from Appendix N are comparable to those found for ECHAM4 here. The HadCM2 results indicate a short term increase of nearly 2 aGW over the baseline. However, this may not be a realistic result because the GCM output was averaged over a shorter period of time (of 10 years), thus allowing decadal variability to skew the results. Over the 10-year period sample for Appendix N, HadCM2 predicts very wet winters—an effect that is attributable to variability within the model, as opposed to a longer term trend toward significantly wetter

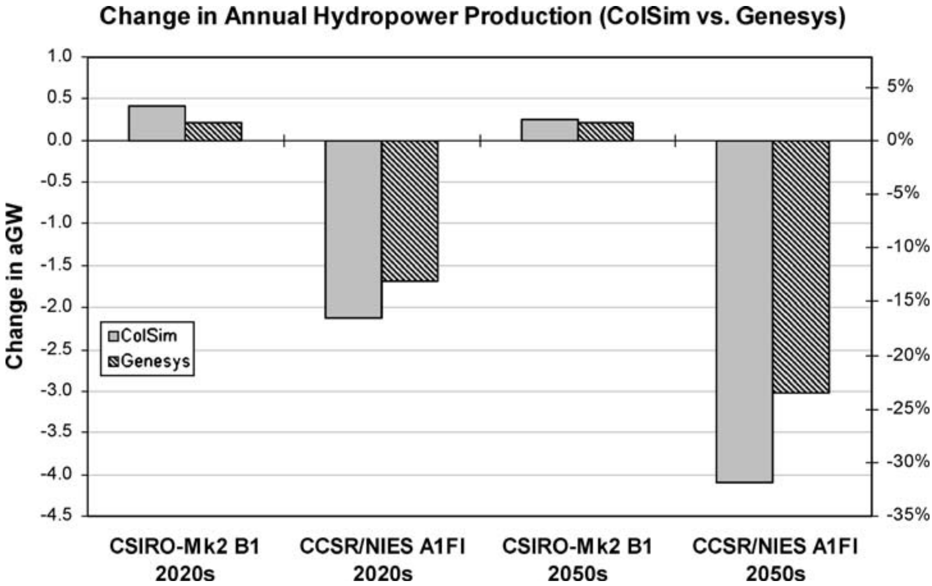

Fig. 5 Change in average annual hydropower production, as simulated by ColSim and Genesys, in aGW for the 2020s and 2050s. The *right axis* is percent of baseline hydropower production, as simulated by ColSim

winters for the PNW. Also, HadCM2 has now been superseded by HadCM3, which is included in the present study. (HadCM3 perturbations over all three time periods result in decreased hydropower potential. For example, see the regression results below for the 2080s.)

Applying the same power prices used in the Appendix N analysis (NWPCC forecast 2006 bulk electricity prices, averaging about $43/MWh), the impact on hydropower

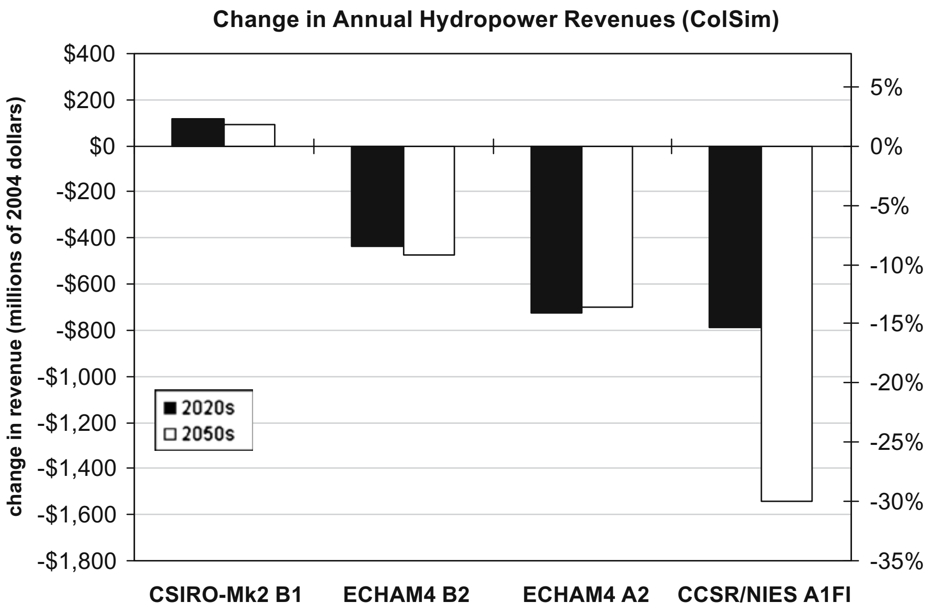

Fig. 6 Hydropower revenues. The *right axis* is percent of simulated baseline revenues

revenues are calculated (see Fig. 6). In Appendix N, the result of this calculation is used to estimate annual benefit to the region. Again, the present results are more pessimistic than the results found by the NWPCC in Appendix N. The HadCM2 scenario in Appendix N is estimated to provide an undiscounted annual benefit of $777 million to the region in the short term. The ‘best case’ short-term scenario in the present analysis (CSIRO-Mk B2) is not nearly as rosy, with a benefit of only $118 million. Furthermore, the ‘worst case’ scenario (CCSR/NIES A1FI) is much worse than Appendix N prepares us for—with an annual revenue loss more than twice as great as that predicted by Appendix N’s ECHAM4 scenario. (The present ECHAM4 results are roughly comparable to the Appendix N ECHAM4 results.) Though not shown in Fig. 6, applying the NWPCC price forecasts to the ‘worst case’ Genesys hydropower predictions (from Fig. 5, above), yields a loss of $622 and $1,071 million in the 2020s and 2050s, respectively.

Caution is recommended in interpreting these results, but particular care may be necessary with the estimated monetization of changes in hydropower generation. Besides the increasing volatility of electricity prices associated with deregulation, there are a number of reasons to be suspicious of long term price forecasts. Nonetheless, it is nearly certain that lower hydropower production will correspond to lower revenues no matter the seasonality. With a change in shape and timing of the hydrograph, and corresponding changes in west coast electricity demand, it is possible that this effect may be mitigated slightly. For large decreases in streamflows such as those implied by ECHAM4 and CCSR/NIES scenarios; however, costs are expected to be very high.

4 Discussion

In addition to the comparison presented in Sect. 3, our results allow a number of other interesting lines of investigation. Below are four simple applications of regression models using the seasonally summarized climate scenario data presented in Fig. 2. These four predictors (precipitation fraction and temperature change, for both winter and summer) are able to capture a surprisingly large fraction of the variability in streamflow changes predicted by VIC, and power generation predicted by ColSim, with adjusted R^2 values above 0.9. For example, a linear regression on average annual flows using the change in winter and in summer temperature and precipitation yields an adjusted R^2 of 0.973 (see Table 3). The 35 data points in the dependent variable correspond to the average annual corrected flow over the period 1915–2003 for each of the scenarios indicated in Table 2, plus the baseline ‘no perturbation’ scenario.

Though only 13 of the 35 scenarios listed in Table 2 were run through ColSim (in particular, the 2020s, 2050s, and 2080s scenarios for ECHAM4 A2, ECHAM4 B2, CCSR/NIES A1FI, and CSIRO-Mk2 B1, plus the baseline ‘no perturbation’ scenario), a regression on these data yields similarly strong results, as shown in Table 4.

Table 3 Regression model used to predict average annual flow

Predictive variables	Standardized coefficients	Significance
Change in winter precipitation	0.630	0.000
Change in summer precipitation	0.366	0.000
Change in summer temperature	−0.404	0.000

Dependent variable: average annual flows at The Dalles as modeled by VIC. Adjusted R square=0.953, N=35.

Table 4 Regression model used to predict average annual hydropower generation

Predictive variables	Standardized coefficients	Significance
Change in winter precipitation	0.459	0.000
Change in summer precipitation	0.412	0.014
Change in winter precipitation	−0.334	0.009

Dependent variable: average annual hydropower generation as modeled by ColSim. Adjusted R square= 0.964, N=13.

4.1 Extended sensitivity analysis

These regression equations form the basis for a sensitivity analysis on a large number of scenarios, as in Fig. 7 showing predicted change in hydropower production for the 2080s.

The 2080s scenarios suggest that a decrease in hydropower potential is likely (see Fig. 7). With the exception of CSIRO-Mk2, and one of the CCCma scenarios, all of the scenarios show a decrease in hydro generation. GFDL and NCAR-PCM show a moderate decline in hydro potential by the 2080s, while all HADCM3 and CCSR/NIES scenarios, as well as ECHAM4 A2, show large declines. Besides the wide range of possible impacts, it is also notable that these estimates are widely distributed. CSIRO-Mk2 B1 and CCSR/NIES A1FI are clearly the extreme cases, but when all of the emissions scenarios are considered, neither model is an obvious outlier.

The utility of this approach is further demonstrated in an analysis of climate scenarios drawn from GCM model runs for the IPCC Fourth Assessment Report (AR4). Climate scenarios for the PNW are calculated for the PNW by Mote et al. 2005, and rapidly assessed using the same regression equation applied in Fig. 7. The results, shown in Fig. 8, suggest that the AR4 scenarios predict slightly less severe impacts in the 2080s to PNW water resources.

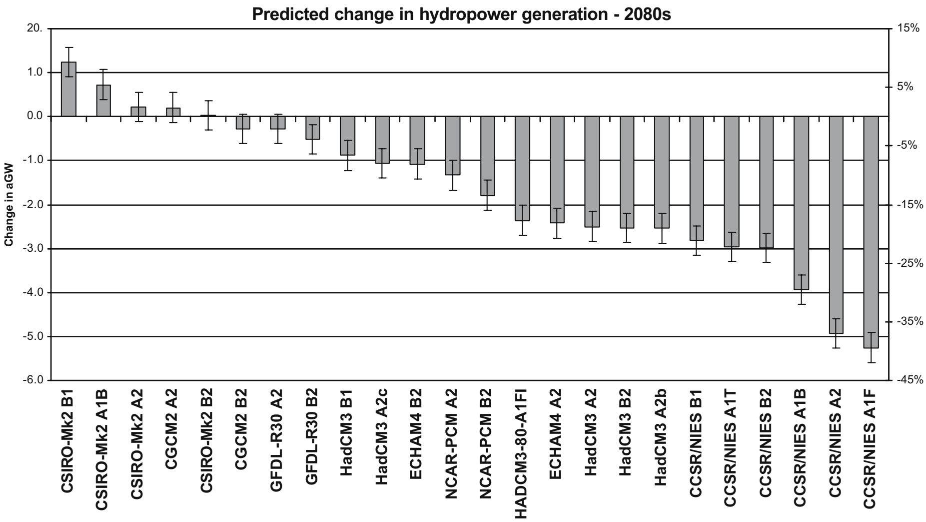

Fig. 7 Predicted change in annual hydropower production, in aGW, using the regression equation (R^2=0.97), for all TAR model and scenario combinations in 2080s. The *right axis* is percent of baseline hydropower production, as predicted by the regression equation. *Error bars* show plus/minus standard error of the estimate (i.e., showing a range of 2× standard error of the estimate)

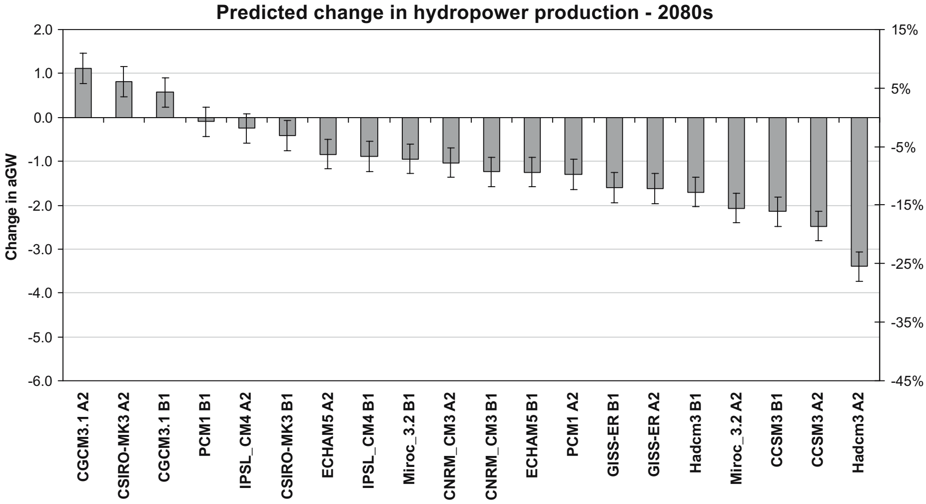

Fig. 8 Predicted change in annual hydropower production, in aGW, using the same regression equation as Fig. 7, for AR4 model and scenario combinations (from Mote et al. 2005) in 2080s. The *right axis* is percent of baseline hydropower production, as predicted by the regression equation. *Error bars* show plus/minus standard error of the estimate (i.e., showing a range of 2× standard error of the estimate)

4.2 Finding contributions to variation and thresholds

The regression equations are also used to explore contributions to variability and threshold conditions. To remove the possible influence of varying emissions pathways, we consider predicted hydropower revenues for all of the A2 scenarios (7 perturbations, one from each model). By first holding temperature to the A2 average and varying precipitation within one standard deviation, and then holding precipitation to the A2 average and varying temperature within one standard deviation, we find that precipitation contributes about three times more variability to the hydropower potential prediction than temperature. This is a particularly interesting result given that the temperature estimates have a higher coefficient of variation (ratio of standard deviation and average) than the precipitation estimates. Consequently, although there is less statistical variation in the GCM estimates of precipitation, further refining precipitation estimates will narrow regional impact predictions more than refining temperature estimates. When analyzed separately, this result holds across each of the three time periods included in this study, indicating that even in the short term, disagreement among GCM precipitation predictions is a large source of uncertainty in impact assessment.

Threshold questions can also be addressed. For example: in the 2020s under the A2 scenario, how much wintertime precipitation is required to maintain current hydropower potential if we assume that the central estimates for temperature change and summer precipitation are correct? This assumption would make sense if, for example, we are relatively confident in the GCM predictions for higher temperatures (average for the A2 2020s perturbations: +1.1°C in the winter and +1.4°C in the summer) and slightly decreased summertime precipitation (average for the A2 2020s perturbations: −3%), but are less confident in model predictions of changes in the important wintertime precipitation. Weighting equally the A2 scenario for the 2020s from each GCM to find the central estimates for temperature change and summer precipitation, the regression indicates that wintertime precipitation must increase by about 9% in order to maintain current hydropower revenues. However, of all the 2020s scenarios, only one predicts such an increase in wintertime precipitation—CSIRO-Mk2 B1, which predicts a 9.4% increase in wintertime precipitation.

4.3 Relative impacts of changes in precipitation and temperature

The relative impact of changes in temperature and precipitation on hydropower generation is further explored in Fig. 9. The 2080s period is selected to show a wide range of predicted temperature and precipitation changes. The data points are the same as those presented in Fig. 7, with the predicted impacts ranging from slight increases to large decreases. As illustrated by the isolines, these data suggest that a 3% change in precipitation has a similar impact on hydropower to a 1°C change in temperature. In other words, every 1°C increase in temperature requires an approximately 3% increase in precipitation to maintain current levels of hydropower generation.

4.4 Effect of emissions pathway on flows

Because the total radiative forcing associated with the emissions scenarios does not begin to diverge significantly until the 2050s, we do not expect the results from individual GCMs to clearly demonstrate sensitivity across emissions scenarios for the 2020s. (However, for the 2020s, the results for each model do vary across emissions scenarios—though this is assumed to primarily the result of ‘random variation’ in response to only slightly different model inputs.)

The effect of diverging emissions scenarios is expected to be most clear for the 2080s. From the scenarios available for each GCM, the scenarios with highest and lowest radiative forcing are selected, and the annual flows as predicted by the regression equation shown in Table 3 are compared. For example, Table 5 shows that for HadCM3, A1FI (a scenario with higher radiative forcing than A2) and B1 (a scenario with lower radiative forcing than B2 in the 2080s) are selected. For the first four GCMs shown in the table, lower flows are predicted for scenarios with higher radiative forcing—indicating that these GCMs tend to predict lower flows with higher levels of greenhouse gas emissions. However, CGCM2

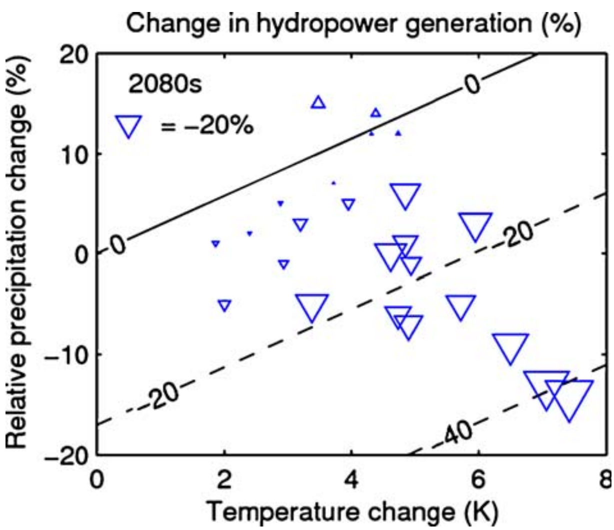

Fig. 9 Predicted change in annual hydropower generation (%) as a bivariate function of change in temperature and precipitation from GCM output for the 2080s. Size of *triangle symbol* indicates magnitude of change in hydropower generation. (The legend shows a triangle corresponding to a 20% decrease. A triangle with sides twice as long corresponds to a 40% decrease.) *Triangles pointing up* represent increases while *triangles pointing down* represent decreases. Isolines of hydropower generation are based on a regression model derived using annual temperature and precipitation change as predictors are plotted at 0, −20, and −40% relative to current levels

Table 5 Annual flows for the 2080s, as predicted by the regression equation from Table 2, for the highest and lowest radiative forcing perturbations for each model

GCM	Scenario	W-prec (%)	W-temp	S-prec (%)	S-temp	Predicted annual flows (10^9 m^3)	Higher emissions cause flows to...
ECHAM4	A2	108	4.20	84	5.48	131.7	↓
ECHAM4	B2	111	3.54	91	4.36	149.7	
HadCM3	A1FI	112	4.33	87	7.58	119.1	↓
HadCM3	B1	108	2.41	95	3.98	145.2	
CSIRO-Mk2	A2	119	5.05	98	4.40	176.1	↓
CSIRO-Mk2	B1	122	3.92	101	3.03	189.2	
CCSR/NIES	A1FI	89	6.86	80	7.99	97.8	↓
CCSR/NIES	B1	97	4.38	90	5.08	128.2	
CGCM2	A2	125	4.39	91	4.23	174.3	↑
CGCM2	B2	111	2.71	96	3.07	161.1	
GFDL-R30	A2	99	2.41	105	2.36	160.2	↑*
GFDL-R30	B2	98	1.72	103	2.01	155.0	
NCAR-PCM	A2	103	3.09	92	2.79	152.7	↑*
NCAR-PCM	B2	99	2.20	88	1.80	147.2	

The standard error of the estimate is 4.1×10^9 m^3, so the differences between the A2 and B2 predictions for the GFDL-R30 and NCAR-PCM model are not statistically significant.

exhibits the opposite effect, while the results for the last two GCMs shown in the table are not conclusive. Although there isn't a clear consensus among the GCMs – even as far out as the 2080s when the emissions scenarios have diverged broadly – as to whether higher levels of emissions will affect annual flows in the CRB positively or negatively, these results do suggest that the risk of increased negative climate impacts probably stays about the same, or increases, with higher levels of radiative forcing. It is clear, however, that the differences between the models – even for the same emissions scenario – are very significant, and highly salient to the evaluation potential of impacts.

5 Recommendations and future directions

This work demonstrates that climate change has the potential to seriously impact the PNW hydropower system, and therefore the region's supply of electricity. Affirming the conclusion of the NWPCC, climate change is an important factor within the 20-year planning horizon and worthy of further study. The NWPCC's Portfolio Model would be sensitive to the range of possible changes in hydroelectric potential found in this study (Fazio, personal communication), implying that a different portfolio of generating resources from that recommended in the 5th Plan would be preferable to protect regional electricity supply from the effects of climate change. Therefore, even if the uncertainty in climate predictions cannot be reduced, the power planning process could be made more robust by quantifying this uncertainty, as has been done here, and representing it in the NWPCC's Portfolio Model.

Further, these results suggest that both top-down and bottom-up approaches (Dessai and Hulme 2004) to impact assessment and adaptation planning for PNW water resources can be streamlined. Because the sensitivity of the hydrologic and reservoir modeling chain to climate scenarios can effectively be captured by a simple regression model, new scenarios can be readily tested and the climate conditions under which impact thresholds important to adaptation planners might be crossed can be identified. Uncertainty in GCM predictions and emissions pathways is likely to persist into the foreseeable future. Therefore, simple models for exploring potential impacts under a range of climate assumptions are of great value (Jones 2001).

Next steps in incorporating climate information in regional power planning should include conducting a sensitivity analysis on the NWPCC's Portfolio Model. The expectation is that including information about climate change will substantially alter the output of the Portfolio Model; however, this assumption warrants testing. Once the Portfolio Model is shown to be sensitive to the range of impacts presented here, a PDF representing these impacts should be constructed for use in the Portfolio Model.

Probability density information may be presented in two ways from results such as the generation potential predictions of Fig. 7. The first method is to construct a histogram of the results assuming uniform likelihood of the model/scenario pairs. For example Fig. 10 presents flow predictions for the 2020s, using the corresponding dataset to that displayed in Fig. 7 for the 2080s. These results suggest a 8.3% chance that climate change will increase regional hydroelectricity generation potential, with the expected value being a loss of over 0.7 aGW.

However, weighting all model/scenario pairs equally is problematic—as the resulting PDF is biased by the number of scenarios run by each model. Further, the emissions scenarios themselves do not constitute a random or representative set, but rather are selected out of interest in particular possible futures without regard to their probability. The second method, maximum entropy inference, strives to generate a PDF restricted by the available information, but no further, minimizing the role of judgment (Shannon and Weaver 1949). In the case under discussion, the maximum likelihood approach could be used to construct a PDF corresponding to the range of the set of predictions, i.e., a uniform distribution between the maximum and minimum values would represent the uncertain quantity. Again

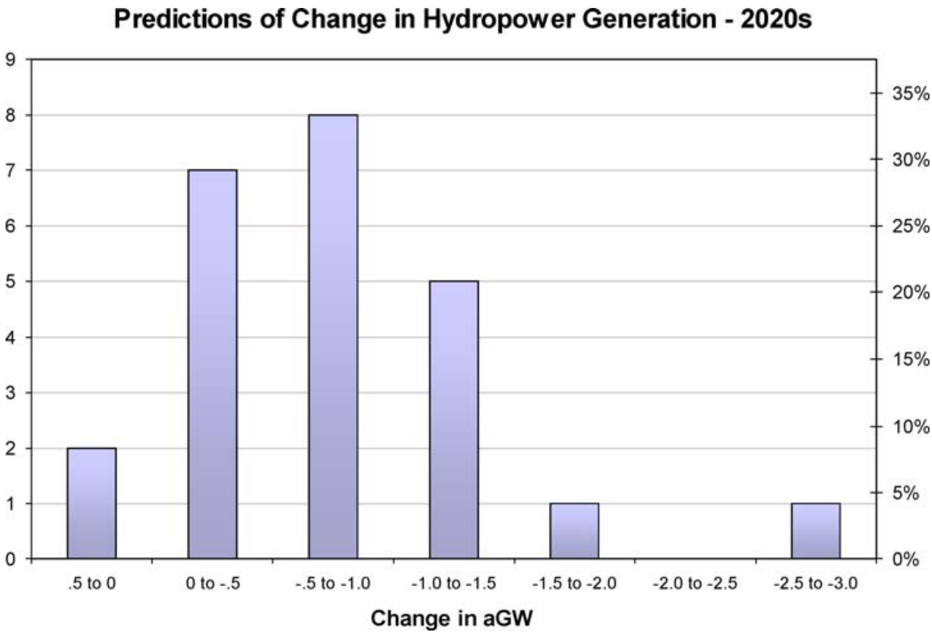

Fig. 10 Histogram showing predictions of change in hydropower production for the 2020s. *Right axis* shows probability expressed as a percent, assuming equal likelihood of all model/scenario pairs

for the 2020s, this yields a PDF that allows a 13% chance that climate change will increase regional hydropower potential, but at the mean expects a loss of 1 aGW.

This approach also falls short due to basic underlying biases. For the reasons discussed earlier it is likely that the present set of model/scenario pairs does not reflect the full range of future possibilities. Thus, any construction of a PDF to represent these results should incorporate additional variability accounting for completely unexpected future occurrences (Jones 2000a). A more complex treatment would necessitate a reliance on statistical tools for dealing with unsuspected errors and gaps in basic understanding, such as those developed by Shlyakhter (1994) for treating "surprise" in future predictions (Cullen and Frey 1999).

Aside from properly addressing surprise, the primary challenge in constructing a PDF more rigorous than those above is the assignment of relative weights to the GCMs. Within the 20-year planning horizon, emissions pathways do not diverge significantly, so each scenario can be considered equally likely for present purposes. Subjective methods have been proposed for assigning weight to results from different GCMs, including the use of model characteristics such as level of sophistication in land surface representation scheme as a criterion (Nijssen et al. 2001), and assigning a predetermined distribution (Prudhomme et al. 2003; Jones 2000b; New and Hulme 2000). A PDF calculated based purely on the GCM outputs themselves and other climate data is perceived to be less subjective, in providing a highly quantitative basis for impact analysis; although judgment is a central feature of any method applied for this purpose (Morgan and Keith 1995). Giorgi and Mearns (2002, 2003) and Tebaldi et al. (2004, 2005) apply two formal criteria in weighting GCMs—a performance criterion, which assigns greater weight to those models that better reproduce climate observations, and a convergence criterion, which assigns greater weight to those models that tend to agree with one another.

The performance criterion could be applied by evaluating the GCMs ability to reproduce twentieth century temperature and precipitation trends observed globally, or regionally, such as in Mote (2003). Assuming the delta method to downscale GCM outputs, errors in GCM predictions of decadal and interannual climate variability can be tolerated (i.e., reproduction of observed variability need not be part of a weighting criterion). Experimenting with other downscaling methods (and, accordingly, more sophisticated performance criteria) might be warranted, but given the uncertainty elsewhere in the modeling chain we believe that the delta method is sufficient. Regarding the convergence criterion, it does not seem necessary to penalize outlier GCMs. For example, CCSR/NIES is clearly an outlier for the 2050s and 2080s (see Fig. 2), predicting much drier winters than other models. Objectively, being an outlier from a population of 7 is not sufficient grounds for reducing a GCM's influence on our assessment of possible climate impacts in the PNW. The CCSR/NIES model may be a poor performer based on a performance criterion, but absent such a result, outlier predictions should be preserved.

In refining estimates of climate change impacts on PNW hydropower beyond the 2020s, economic evaluation outside the Portfolio Model analysis is likely to be used. The valuation of lost hydropower generation is a complex economic problem with uncertainties and feedbacks not explored here. Further, uncertainty related to hydrologic modeling (VIC, in this case) might be explored in future work. Though VIC is a sophisticated land-surface hydrology model, its results are adjusted significantly by the bias correction procedure that is geared toward reproducing observations.

This work supports continued scientific research to improve understanding of the effect of climate change on global and regional patterns of precipitation. This study shows that precipitation is the most important source of uncertainty derived from GCM predictions, thus improved skill in forecasting this variable has the potential to greatly improve decision making. As such we support the suggestions on research priorities outlined in the scientific consensus statement from the Impacts of Climate Change on the PNW scientific conference (Oregon State University 2004) that identifies trends and patterns in precipitation as a key area that should be addressed by further basic research.

We also believe this work bolsters the argument that the PNW has a significant economic interest in policies that reduce anthropogenic greenhouse gas emissions and thus minimize our commitment to additional future climate change (Resource Innovations 2005; Washington Economic Steering Committee and the Climate Leadership Initiative 2006). Further, unlike much of the rest of the United States, reducing electricity consumption in the PNW is not only a necessary component of global climate change mitigation, but also a prudent regional adaptive measure in response to climate change risk.

Acknowledgements This research was funded by the TSP program at the University of Washington. Assistance and support with the VIC and ColSim models from Nathalie Voisin, Alan Hamlet, and Dennis Lettenmaier is gratefully acknowledged. Further we wish to acknowledge support with Genesys model runs and insightful feedback from John Fazio at the NWPCC. We acknowledge the EOS computer facility in the University of Washington Department of Atmospheric Science and Marc Michelsen for providing valuable computing resources. Thanks to Chris Bretherton, Roger Jones, Philip Mote, Eric Salathé, and Justin Wettstein for helpful advice, and additionally to Chris for drafting Figs. 3 and 10. Finally, thanks to two anonymous reviewers for their careful reading. Any and all errors remain the responsibility of the authors.

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