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Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State

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Abstract Climate strongly affects energy supply and demand in the Pacific Northwest (PNW) and Washington State (WA). We evaluate potential effects of climate change on the seasonality and annual amount of PNW hydropower production, and on heating and cooling energy demand. Changes in hydropower production are estimated by linking simulated streamflow scenarios produced by a hydrology model to a simulation model of the Columbia River hydro system. Changes in energy demand are assessed using gridded estimates of heating degree days (HDD) and cooling degree days (CDD) which are then combined with population projections to create energy demand indices that respond both to climate, future population, and changes in residential air conditioning market penetration. We find that substantial changes in the amount and seasonality of energy supply and demand in the PNW are likely to occur over the next century in response to warming, precipitation changes, and population growth. By the 2040s hydropower production is projected to increase by 4.7–5.0% in winter, decrease by about 12.1–15.4% in summer, with annual reductions of 2.0–3.4%. Larger decreases of 17.1–20.8% in summer hydropower production are projected for the 2080s. Although the combined effects of population growth and warming are projected to increase heating energy demand overall (22–23% for the 2020s, 35–42% for the 2040s, and 56–74% for the 2080s), warming results

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in reduced per capita heating demand. Residential cooling energy demand (currently less than one percent of residential demand) increases rapidly (both overall and per capita) to 4.8–9.1% of the total demand by the 2080s due to increasing population, cooling degree days, and air conditioning penetration.

1 Introduction

On average approximately 70% of electrical energy consumption in the Pacific Northwest (PNW) is generated by hydropower (Bonneville Power Administration 1994). Because streamflow, mostly within the Columbia River basin, is the main power source, its climatic sensitivity has been a concern, and has been the topic of several previous studies (Hamlet and Lettenmaier 1999; Payne et al. 2004; NWPCC 2005). Regional hydropower production in the Columbia River basin has a profound impact on Washington's energy supply. A number of Public Utility Districts (PUDs) in Washington, for example, receive the majority of their power from the Bonneville Power Administration (BPA), which markets most of the Columbia River's hydropower production. Snohomish County PUD, to give one example, currently receives about 88% of its electrical energy resources from the BPA (http://www.snopud.com/energy/pwrsource.ashx?p=1878#fuelmix, 13 Dec 2008). Links between climate and the demand for electric power and fossil fuels (such as natural gas) have been explored in past studies (e.g. Sailor and Munoz 1997; Voisin et al. 2006; Westerling et al. 2008), and recent studies have examined the potential implications of climate change on demand for electrical power (Sailor and Pavlova 2003; NWPCC 2005).

In addition to direct effects to energy supply (for instance, changes in the seasonality and annual volume of streamflow supplying hydropower projects), there are a number of indirect effects of climate on hydropower supply and electrical power demand. These include a) changes in hydropower production related to climate change adaptation for other water management objectives (e.g. changes in flood control operations or attempts to adapt to losses of instream flow in summer), b) climate related effects to fossil fuel costs or availability, c) climate related effects on renewable energy resources such as wind turbines or photovoltaic cells, and d) shifts in population that may be partly related to changes in climate or water supply.

In this paper, we analyze projected future changes in energy supply and demand in the PNW that specifically affect Washington State (WA). In particular, we address the following research questions:

- How will seasonal and annual total hydropower production from the Columbia River basin change over the next century in response to projected warming and changes in precipitation?
- How will heating and cooling energy demand change over the next century in response to warming and population growth?
- How do electrical peak energy demand sensitivities to temperature compare in the PNW and California, and how can this information be used to understand potential changes in peak energy demand in the region related to warming?

Following methods common to the other investigations in this special issue, we examine the effects of climate change projected for future conditions in the 2020s

(2010–2039), 2040s (2030–2059), and 2080s (2070–2099) for two IPCC greenhouse gas emissions scenarios (A1B and B1; Nakićenović and Swart 2000; Mote and Salathé 2010).

2 Methods

We summarize briefly in this section the main aspects of the methods used to address the research questions outlined above.

2.1 Temperature and precipitation scenarios

We used composite delta method temperature and precipitation scenarios which are spatial (regional) and temporal (monthly) averages of climatic changes simulated by 20 global climate models (GCMs) for three future time periods (2010–2039, 2030–2059, and 2070–2099) and two emissions scenarios (A1B and B1; Mote and Salathé 2010). The combination of three time periods and two emissions scenarios results in six delta method climate change scenarios, which we will refer to as composite scenarios. The composite monthly average temperature and precipitation projections for each time period and each emissions scenario are given in Table 1. Around these mean projections of future climate there is a range of temperature and precipitation changes simulated by different climate models for different time periods due to both differing GCM sensitivity to greenhouse forcing and simulated decadal sequencing of precipitation and temperature variability (Mote and Salathé 2010). These uncertainties notwithstanding, the composite scenarios represent a consensus prediction of systematic changes in PNW climate that affect energy supply and demand.

Table 1 Summary of temperature and precipitation changes for six composite climate change scenarios

Scenario	J	F	M	A	M	J	J	A	S	O	N	D
Temperature change relative to late twentieth century values (Future minus late twentieth century temperature in degrees Celsius)												
2020A1B	1.22	0.99	1.11	0.99	1.01	1.28	1.59	1.60	1.37	1.00	0.83	1.17
2020B1	1.10	1.08	1.11	1.03	1.01	1.06	1.34	1.30	1.21	0.99	0.79	1.01
2040A1B	1.99	1.75	1.90	1.74	1.68	2.13	2.79	2.72	2.50	1.86	1.56	1.94
2040B1	1.49	1.41	1.46	1.45	1.37	1.44	2.05	2.05	1.90	1.37	1.17	1.65
2080A1B	3.59	3.25	3.22	2.87	2.69	3.66	4.59	4.73	4.20	3.15	2.85	3.40
2080B1	2.53	2.39	2.27	2.23	2.04	2.49	3.07	3.22	2.91	2.14	2.12	2.53
Future precipitation expressed as a fraction of late twentieth century values												
2020A1B	1.00	1.00	1.02	1.01	0.99	0.94	0.90	0.90	0.91	1.02	1.06	1.03
2020B1	1.01	0.99	1.03	1.03	1.00	0.99	0.99	0.97	0.94	1.07	1.06	1.04
2040A1B	1.04	1.01	1.06	1.06	0.99	0.90	0.85	0.88	0.87	1.07	1.08	1.06
2040B1	0.99	1.00	1.06	1.03	1.02	0.99	0.95	0.91	0.94	1.05	1.07	1.07
2080A1B	1.06	1.07	1.11	1.09	1.00	0.89	0.82	0.78	0.92	1.13	1.11	1.11
2080B1	1.05	1.03	1.03	1.06	1.03	0.93	0.89	0.84	0.95	1.07	1.09	1.09

2.2 Estimates of regional scale hydropower production

To estimate hydropower resources in the Columbia River hydro system, streamflow impacts for the entire Columbia River basin must be estimated. Here we use results produced by a 1/16th degree implementation of the VIC hydrologic model (Liang et al. 1994) implemented over the Columbia River basin to predict changes in streamflow over the next century relative to a baseline period of 1917–2006 water years. Elsner et al. (2010) describe the VIC model implementation, and the model forcing data sets. VIC streamflow simulations were bias adjusted at monthly time scales using methods described by Snover et al. (2003). Historical "modified" streamflow data sets (which are estimates of the flows that would have occurred in the absence of the reservoir system, adjusted for a consistent level of consumptive water use for irrigation), used to train the bias adjustment process, were originally prepared for the BPA and cover the period 1928–1999 (BPA 2004). The overlapping simulated and observed streamflow data (1928–1999) are used to train the bias correction procedure, but the final bias correction process is applied to the entire VIC streamflow simulation (1917–2006 water years) to produce a 90 year input time series for the ColSim reservoir model. As discussed below, updated flood rule curves and refill curves are then constructed within ColSim based on this new streamflow time series.

To estimate hydropower production, the ColSim reservoir simulation model (Hamlet and Lettenmaier 1999; see also Fig. 1) was used to simulate reservoir operations resulting in energy production at 20 major projects in the basin for a historic baseline period of water years 1917–2006 (1 year, 1916, required for spin-up), and the same group of water years extracted from the future delta-method scenarios described above. Hamlet and Lettenmaier (1999) describe the model in more detail, but in brief it simulates the operation of the multi-objective reservoir system, including hydropower production, flood control, irrigation withdrawals in the Snake Basin, and instream flow augmentation for fish in the mainstem and tributaries. By linking the model to different streamflow scenarios, the effects of altered hydrologic variability on system-wide energy production are estimated. The model includes some basic adaptive responses associated with flood control (i.e. the amount of flood evacuation and reservoir refill curves that affect hydropower releases are automatically adjusted in the model as a function of changing summer flow volumes), but in general the reservoir operating policies (including monthly energy targets for "firm" and "non-firm" energy in the model, which are derived from historic analyses) are held fixed in these experiments. Thus the simulation framework represents very limited adaptive responses related primarily to improved streamflow forecasting that takes into account ongoing warming in estimating summer streamflow volumes. Other potential adaptation alternatives are discussed by Whitely Binder et al. (2010).

The effects of potentially changing seasonal energy demand on the reservoir model simulations merits some further discussion. Currently, hydropower resources supply approximately 70% of the electrical energy demand in the PNW (BPA 2004). Because hydropower usually represents the least expensive source of energy, the amount of energy that is extracted from the Columbia River hydro system is not strongly related to year-to-year demand variations, but is instead controlled primarily by water availability (i.e. the "fuel" of the hydropower resource is the limiting factor). To be sure, in a given operational year, seasonal variations in demand may play a

Fig. 1 Columbia River basin projects incorporated in the ColSim reservoir model (Note Snake River projects are aggregated in the model). Figure: Robert Norheim

significant role in the way the reservoir system is operated. Here, however, where long-term averages of hydropower production over a 90-year simulation period (1917–2006 water years) are reported, these short-time-scale operational effects can probably be neglected without affecting the outcomes in any material way. For example, if summer energy demand increases (as projected in subsequent sections of this paper), there is currently little ability to further draft storage reservoirs to meet these needs because of other system constraints. The same cannot be said for conventional fuel-based energy resources that must supply the remaining demand for power over and above what can be supplied by hydropower and other renewable resources.

Several elements of actual operations are not simulated by the ColSim model. These include the effects of intentional spill from some dams in spring to facilitate juvenile fish passage, and reservoir releases to maintain acceptable levels of water temperature or dissolved gas content. While these are important operational elements in terms of maintaining acceptable conditions for fish, the effects on climate-related changes in system-wide hydropower production (e.g. the percent reduction in summer hydropower production) associated with these operational elements are probably negligible.

2.3 Estimates of heating and cooling energy demand drivers

In many previous analyses (e.g. NWPCC 2005; Sailor and Munoz 1997; Voisin et al. 2006), energy demand has been estimated using aggregated population, temperature (or heating/cooling degree days) and energy use data for large urban centers. While this approach certainly makes sense given the concentration of PNW population in a few urban centers (Fig. 5), here we take the more fundamental approach of estimating population, heating and cooling degree days, and air conditioning market penetration in a gridded format at 1/16th degree latitude by longitude resolution (about 5 by 6.5 km, or roughly 32.5 km^2 area). These gridded data are then used to create a gridded heating energy demand index (HEDI) and cooling energy demand index (CEDI) for each grid cell. HEDI is a function of population and heating degree days (HDD), and CEDI is a function of population, cooling degree days (CDD), and residential air conditioning market penetration (A/C_Pen, defined below). The indices are defined as follows:

$$\text{HEDI} = \text{Population}^{*}(\text{Annual Heating Degree Days}) \tag{1}$$

$$\text{CEDI} = \text{A/C\_Pen}^{*}\text{Population}^{*}(\text{Annual Cooling Degree Days}) \tag{2}$$

where A/C_Pen is the estimated total residential air conditioning market penetration (i.e. the fraction of the population that has access to either central or window air conditioning) for each grid cell, estimated as a function of annual CDD (Sailor and Pavlova 2003, Eq. 4):

$$\text{A/C\_Pen}\,(\text{CDD}) = \left(0.944 - 1.17^{\,*} \exp\left(-0.00298^{*}\text{CDD}\right)\right) \tag{3}$$

A minimum value of A/C_Pen of 0.08 was imposed to reflect the fact that at relatively low CDD values air conditioning market penetration is less strongly determined by CDD and is generally not zero (Sailor and Pavlova 2003).

This overall approach has several advantages. First, the climate sensitivity of the indices are primarily physically based, which avoids assumptions of parameter stationarity for future projections (unlike regression-based approaches trained on observed data). Second, it facilitates aggregation of the data in different ways after the fact: allowing, for example, an assessment of rural areas or smaller towns as well as large urban centers. Third, it facilitates the use of more detailed representations of changing population, or changes in energy use patterns that have substantial geographic variations. Separating the influence of population and climate on energy demand also facilitates a clearer representation of the changes related to each, and facilitates the construction of qualitative scenarios that explore a range of uncertainties (a few simple variations of which we explore in this paper). We note that effects of potentially changing energy use efficiency are not included in the analysis, although this would be a beneficial analysis in the future to evaluate the effectiveness of various adaptation strategies related to conservation and demand management (see Whitely Binder et al. 2010).

We computed gridded estimates of long-term average heating and cooling degree days for a baseline period of 1970–1999, and then performed the same calculations for six future scenarios (discussed above) based on the same group of years. Daily average temperatures (approximated as the average of maximum and minimum daily temperature extremes) were extracted from a gridded 1/16th degree meteorological driving data set. These data are derived from gridded station data, and topographic adjustments were made using products from the precipitation regression on independent slopes method (PRISM; Daly et al. 1994). The methods used in producing these meteorological data sets are described in more detail by Hamlet and Lettenmaier (2005) and Elsner et al. (2010).

Heating degree days (HDD) and cooling degree days (CDD) are calculated in the usual manner for each day as follows:

$$HDD = \max\left(0, 18.33 - \left[\frac{t\max + t\min}{2}\right]\right) \tag{4}$$

$$CDD = \max\left(0, \left[\frac{t\max + t\min}{2}\right] - 23.89\right) \tag{5}$$

where $t\max$ and $t\min$ are maximum and minimum daily temperatures in degrees Celsius, respectively.

These daily values are then aggregated to annual values. Summary results for WA alone were compiled by averaging HEDI and CEDI values for all cells in WA. At the time of this writing gridded 1/16th degree meteorological data were not available for part of the domain in the Puget Sound Lowlands (primarily Island County and San Juan County), and these areas were excluded from the analysis.

Although providing a transparent and largely physically based approach for estimating fundamental energy demand drivers, a number of potential limitations associated with the methods outlined above should be mentioned. HDD and CDD are imperfect measures of per capita energy demand for space heating and cooling, which varies with economic status, building size and design, solar and appliance loads, efficiency of end-use technology, and other factors. Temperature thresholds for calculating HDD and CDD may not be stationary in time, and there is some evidence of acclimatization to warmer conditions which may influence the interpretation of these data (Sailor and Pavlova 2003). Estimates of air conditioning market penetration, although shown to be strongly related to CDD, are subject to many different factors including variations in economic status, cost of energy, prevalence of new construction in a given area, etc. The estimates included here may underestimate market penetration in relatively affluent areas such as the major population centers west of the cascades and in the Spokane and Tri-Cities metropolitan areas, and overestimate market penetration in less affluent areas. Changes in air conditioning market penetration may not progress steadily through time (as we assume here), and instead may emerge in response to extreme heat waves or other factors.

2.4 Population data

Several sources of future population projections are available for WA. At the county level, population projections have been prepared in support of the WA Growth Management Act (GMA; http://www.ofm.wa.gov/pop/gma/projections07.asp, 13 Dec 2008, medium estimates) to 2030. These data are arguably the most carefully prepared projections of changing population in WA, but proved cumbersome given their relatively coarse spatial resolution (roughly 60 km). Therefore, we used a hybrid approach based on gridded 1/16th degree global population estimates for 2000, which we rescaled to match the GMA county estimates of population for 2000 and 2025 over WA. Gridded 2000 population estimates were extracted from high resolution Gridded Population of the World, version 3 (GPWv3) global data sets (CIESIN 2005; Balk and Yetman 2004) and were regridded and aggregated to the 1/16th degree spatial resolution of the climate data (described above). Population growth rates for each county were estimated by comparing medium GMA 2000 population estimates to medium GMA 2025 population estimates. Population estimates for 2045 and 2085 were then projected as a linear extension of the estimated population growth rate from 2000 to 2025 for each county using the medium estimate GMA data sets. Finally, the gridded population data at 1/16th degree for 2000 were rescaled to match the new population estimate in each county for each future time period. Scenarios of population growth after 2025 are based on: a) a simple assumption of continued linear growth using the rate calculated above through the end of the century, and b) a scenario in which we assume that population continues to grow linearly until 2045, but stays at this level through the end of the century. We should note that population estimates are very uncertain at these long time scales and also lack an appropriate scientific basis (the practical limits of trend extension methods are perhaps one or two decades). Nonetheless, these scenarios are instructive in the context of a sensitivity analysis, which is their intended use.

2.5 Estimates of peak electrical energy demand as a function temperature

Using multiple linear regression approaches, Voisin et al. (2006) estimated electrical energy demand in the PNW and California (CA), using population-weighted temperature data as the primary explanatory variable. Westerling et al. (2008) refined these methods to produce nonlinear relationships between temperature and regional peak electrical energy demand in both the PNW and CA. In both cases, the relationships are based on hourly electrical energy data supplied by utilities to the Federal Energy Regulatory Commission (FERC) under its 714 reporting requirements. We primarily use these relationships as a means to understanding potentially changing peak energy demands (related particularly to increased use of air conditioning) in the PNW which may accompany systematically warmer temperatures.

3 Results and discussion

3.1 Changes in regional hydropower production

As discussed by Elsner et al. (2010), changes in temperature and precipitation (Table 1) expected in the twenty-first century will have profound implications for the timing and volume of streamflow in the PNW. Changes in streamflow will have important implications for regional-scale electrical energy supply. As discussed above, we examine these changes using model simulations of Columbia River basin hydropower production.

Hydropower production in the Columbia River basin is strongly correlated with modified streamflow in the Columbia River at The Dalles, OR. Figure 2 shows simulated monthly average mean flow at The Dalles, associated with twentieth century climate and the three A1B and B1 scenarios. Consistent with previous studies (Hamlet and Lettenmaier 1999; Payne et al. 2004; NWPCC 2005), warming produces increased flow in winter, reduced and earlier peak flows, and systematically lower flows in summer (Fig. 2). Although the seasonal shifts in streamflow timing are strongly related to warming and resulting changes in snow accumulation and melt (Elsner et al. 2010), the projected increases in cool season (Oct–March) precipitation and decreases in warm season precipitation in the scenarios (see Mote and Salathé 2010) exacerbate these seasonal effects. In the absence of warming, increases in cool season precipitation would increase annual flow (Hamlet and Lettenmaier 1999; Elsner et al. 2010). In the streamflow scenarios, however, small reductions in annual flow at The Dalles (2–4% by mid-twenty-first century) result from the combination

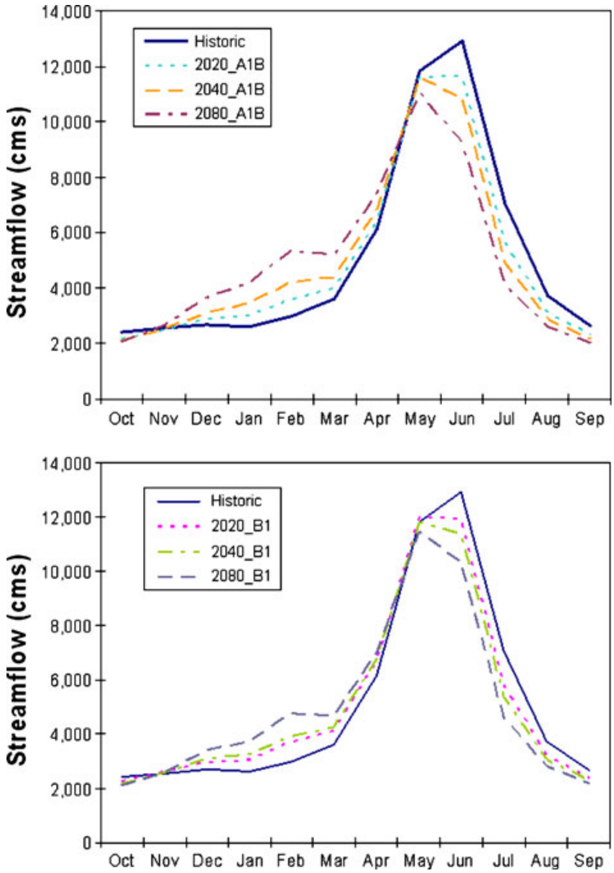


Fig. 2 Simulated long-term mean modified streamflow for the Columbia River at The Dalles, OR for six climate change scenarios. *Top panel* shows results for the A1B scenario. *Bottom panel* shows results for the B1 scenario

of warmer temperatures (increased annual evaporation) and increased cool season precipitation.

Simulated changes in system-wide energy production (without substantial adaptive responses to reservoir operations) largely follow the patterns of altered annual flow and streamflow seasonality. Figure 3 shows long-term mean system-wide energy production for the twentieth century climate compared to the A1B and B1 climate change scenarios (note that each trace in the plot is an average, by month, over 90 simulated years). These results broadly corroborate the findings of previous studies (Hamlet and Lettenmaier 1999; NWPCC 2005).

Table 2 summarizes the changes in long-term mean hydropower production by season as a percentage of the twentieth century values, and as an absolute value from the simulations. As expected, the simulations show increased hydropower production in cool season and decreases in warm season. Changes in annual hydropower production are relatively modest (a few percent) and essentially follow the small reductions in simulated annual flow at The Dalles. The largest changes in hydropower production occur in June and July, which coincides with peak seasonal air conditioning loads (Voisin et al. 2006; Westerling et al. 2008).

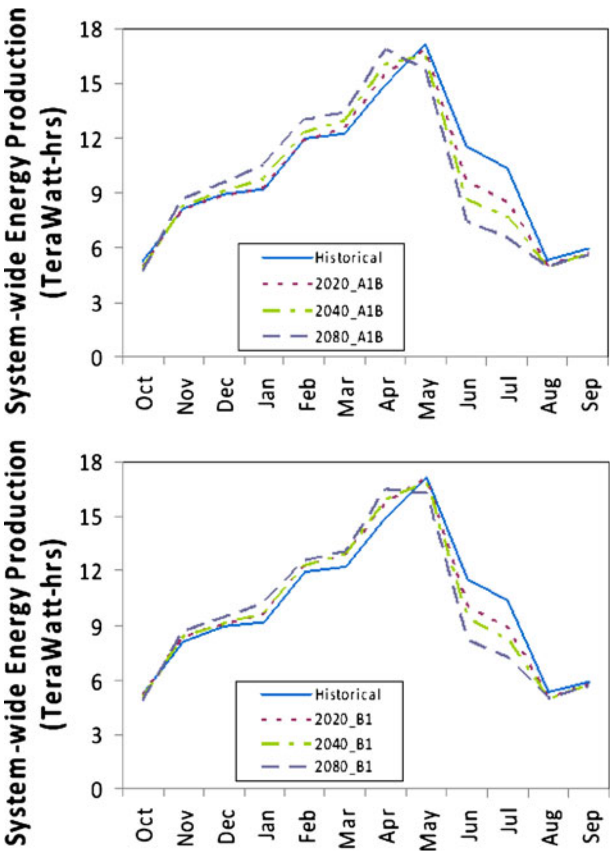


Fig. 3 Simulated long-term mean, system-wide hydropower production from the Columbia River basin for six climate change scenarios. *Top panel* shows results for the A1B scenario. *Bottom panel* shows results for the B1 scenario

Table 2 Summary of simulated hydropower production. Upper table: percent of historic base case. Lower table: total simulated hydropower production (TeraWatt-hrs)

	Annual	OND	JFM	AMJ	JAS
Historic	100.00	100.00	100.00	100.00	100.00
2020A1B	96.63	98.05	101.04	96.29	89.04
2020B1	99.23	101.26	104.53	98.04	91.36
2040A1B	96.62	99.41	104.96	94.78	84.65
2040B1	98.02	100.91	104.66	96.51	87.86
2080A1B	96.85	102.82	110.87	91.83	79.24
2080B1	97.43	102.90	107.69	93.99	82.94
Historic	120.98	22.30	33.38	43.62	21.68
2020A1B	116.90	21.86	33.72	42.00	19.31
2020B1	120.04	22.58	34.89	42.77	19.81
2040A1B	116.89	22.16	35.03	41.34	18.35
2040B1	118.58	22.50	34.93	42.10	19.05
2080A1B	117.17	22.92	37.01	40.06	17.18
2080B1	117.87	22.94	35.94	41.00	17.98

3.2 Changes during drought years

Changes in extremes during drought are also evident in the simulations, and largely follow the changes in mean energy production in each month discussed above. For simulations of critical drought years (e.g. water years 1937, 1977, 2001), cool season hydropower production under climate change scenarios is comparable to the twentieth century simulation, whereas the warm season (defined as April–September) hydropower production is lower than in the twentieth century drought years. These results support the hypothesis that the impacts of future droughts in cool season will be comparable to those in the twentieth century (mitigated both by use of storage, increased cool season precipitation, and a shift toward increased winter runoff due to reduced snowpack). Drought impacts in spring and summer, however, are exacerbated in the simulations, with lower energy production occurring for these seasons for warmer conditions. Loss of runoff from glacial melt (which is not included in the VIC simulations) may exacerbate impacts to late summer low flow and energy production, especially during critical drought years.

3.3 Uncertainties related to decadal precipitation variability

Mote and Salathé (2010) have shown that systematic changes in PNW annual precipitation are projected to be modest over the next century (also see Table 1). Furthermore these systematic changes are relatively small in comparison with observed decade-to-decade variations in twentieth century precipitation. One can conclude that precipitation variability at decadal time scales is therefore an important source of uncertainty in the assessment of impacts for any given decade in the future. Although twenty-first century patterns of decadal variability may be different than the twentieth century ones, nonetheless twentieth century patterns of decadal variability provide a useful basis for assessing these kinds of uncertainties. An analysis of simulated hydropower production for the 2020A1B scenario for the relatively wet period (1947–1976) associated with the cool phase of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), compared to the relatively dry period (1977–2004) associated with the warm phase of the PDO showed that only the changes in energy production in June, July, and August were consistently different from the historic base case when decadal variations were considered. As warming intensifies in the twenty-first century, however, the importance of decadal precipitation uncertainties declines and streamflow timing shifts associated with warming become the dominant effect. This change in the importance of precipitation uncertainties occurs around the 2040s in our analysis (see also Hamlet and Lettenmaier 1999 for a similar analysis of decadal climate variations on future projections).

Although not considered here in detail, changes in the year-to-year variability and/or time series behavior of streamflows as the climate system evolves over several decades could have some important implications for long-term planning. Currently, streamflow forecasts reflecting interannual variability are only available with lead times of perhaps 12 months (e.g. based on ENSO forecasts) and credible forecasts of decadal climate variability associated with the PDO (or other factors) have so far not been developed. These fundamental uncertainties notwithstanding, predominantly warm or cool phase PDO conditions in the next several decades could materially affect outcomes related to energy supply. Methods from stochastic hydrology might present a viable approach for examining these uncertainties in the transient response of the climate system, but these ideas are in the realm of future research needs.

3.4 Tradeoffs between impacts to hydropower production and impacts to other system objectives

In some past studies (e.g. NWPCC 2005) the performance of the Columbia River hydropower system in response to climate change scenarios has been largely dissociated from impacts to other system objectives (such as flood control, or instream flow augmentation for fish). This analysis is potentially misleading, because it ignores the potential for future adaptation in response to other system impacts that may indirectly impact energy production. As an illustration of this point, Fig. 4 shows a probability of exceedance plot of simulated regulated monthly outflows in August at Priest Rapids Dam from ColSim model simulations. (Flows at this location are associated with instream habitat in the ecologically important Hanford Reach of the

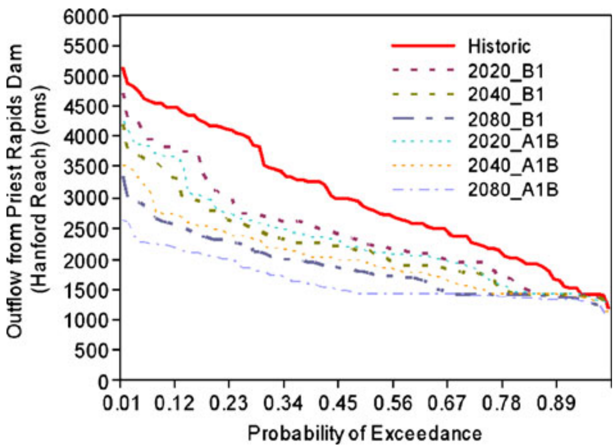


Fig. 4 Probability of exceedance plot of simulated regulated flow in the Hanford Reach of the Columbia River in August for historic conditions and six climate change scenarios

Columbia River). As warming increases and summer streamflow volumes decline, simulated regulated summer streamflow becomes increasingly impacted. Although the model is using more storage to support minimum monthly flow targets at this location (~1420 cms) more substantial adaptive responses to mitigate these impacts would require a much larger increase in the use of reservoir storage on a basin-wide scale, which in turn would impact energy production. Payne et al. (2004) showed, for example, that there were unavoidable tradeoffs between increasing storage allocation to support fish flows and "firm" energy resources in winter due to impacts on reservoir storage levels.

Changes in flood control operations are also expected in response to generally reduced flood risks in the Columbia main stem and streamflow timing shifts towards earlier peak flows (Lee et al. 2009; Mantua et al. 2010). Lee et al. (2009) demonstrate that the use of current flood control rule curves in warmer conditions will impact reservoir refill, and propose optimization approaches for rebalancing flood control and reservoir refill in a warmer climate. Improving reservoir refill ultimately benefits both hydropower production (by increasing volumetric efficiency of energy production) and instream flow augmentation for fish. Lee et al. (2009), however, showed that even with altered flood rule curves there will be some impacts to refill timing. This is most evident at sensitive projects like Dworshak. The study showed that it was possible to successfully fill this project, but only earlier in the season. Thus the ability to achieve full storage at the end of June (a common objective in the Columbia system) is likely to be impacted, even if flood rule curves are adjusted appropriately. Lee et al. (2009) also showed that some improvement in fish flows was possible with altered flood rule curves, but that substantial impacts remained that could not be addressed via this pathway. Payne et al. (2004) reached similar conclusions using a different methodology.

Research to develop more fully integrated adaptation strategies in response to these complex tradeoffs between hydropower production and other system objectives is needed to better understand the combined impacts to regional energy supply. Such tradeoffs will also materially affect transboundary relationships between Canada and the US associated with the Columbia River Treaty (Hamlet 2003). Improved tools to assess these tradeoffs will be needed to inform the negotiations between Canada and the US regarding the future of the Treaty.

3.5 Population

Figure 5 shows gridded estimates of year 2000 population in WA. Most of the population is localized in urban centers in the Interstate-5 corridor in western WA, the Tri-Cities metropolitan area in south-central WA, and the Spokane metropolitan area in the eastern-most part of the state. Thus the dominant climatic influences on state-wide energy demand are focused in a few relatively small geographic areas. Projections of population change are uncertain and vary throughout the state by county according to the GMA assessments discussed above, but projected changes are relatively consistent in the large population centers in WA, where projected changes vary from about 13–17% per decade from 2000–2025. Population is assumed to grow only in currently populated areas in the gridded data sets.

It is worth noting that projections of population past the 2020s lack a credible scientific basis and are an important source of uncertainty in energy analysis at

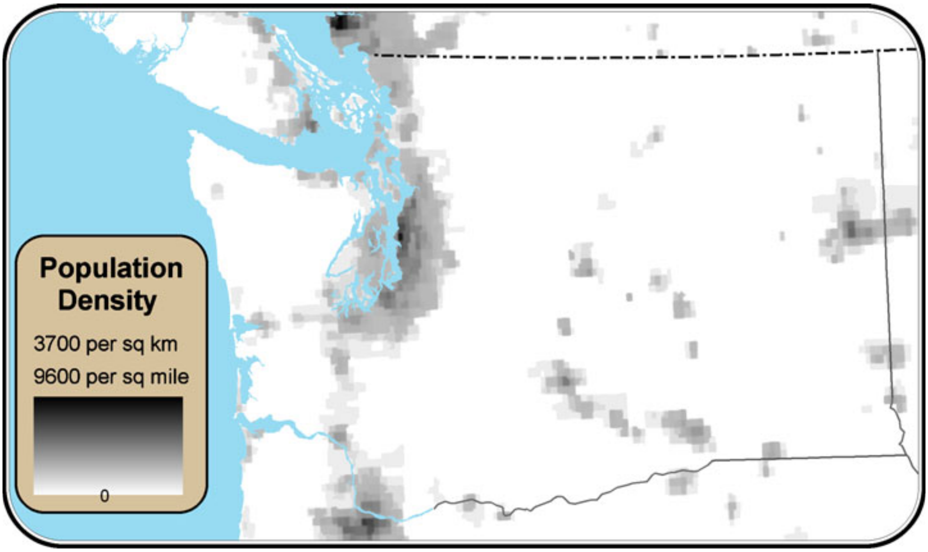


Fig. 5 Gridded population estimates for WA for the year 2000. Units: population density in persons per square km. Each grid cell is approximately 32 km^2. Figure: Robert Norheim

time scales relevant to climate change investigations. Future research using new approaches and methods will be needed to address these concerns.

3.6 HDD, CDD, and air conditioning market penetration

Figure 6 shows long term average HDD, CDD, and A/C penetration calculated for historic data (1970–1999) for WA. Figures 7, 8, 9 show the same estimates for WA for six climate change scenarios (three time periods and two emissions scenarios discussed above). HDD estimates show relatively homogeneous changes throughout the region as winter temperatures warm (Fig. 7). CDD estimates, however, show more localized changes in central WA (Fig. 8). A/C penetration, which is a non-linear function of CDD, largely follows the changes in CDD. CDD and A/C penetration in western WA are relatively insensitive to warming in the 2020s and 2040s, because temperatures mostly remain below the daily average CDD threshold of 23.89°C (75°F), even for a warmer climate. By the 2080s, however, substantial changes in CDD and A/C market penetration are apparent even in the cooler areas of WA.

3.7 Scenarios of HEDI and CEDI

In this section we estimate the sensitivity of HEDI and CEDI to population growth and factors related to warming (changing HDD, CDD and air conditioning use), and then project the combined effects of population growth and warming. Given the great uncertainties related to population projections at the end of the twenty-first century, we also estimate HEDI and CEDI using a qualitative scenario-based approach discussed below (Table 3).

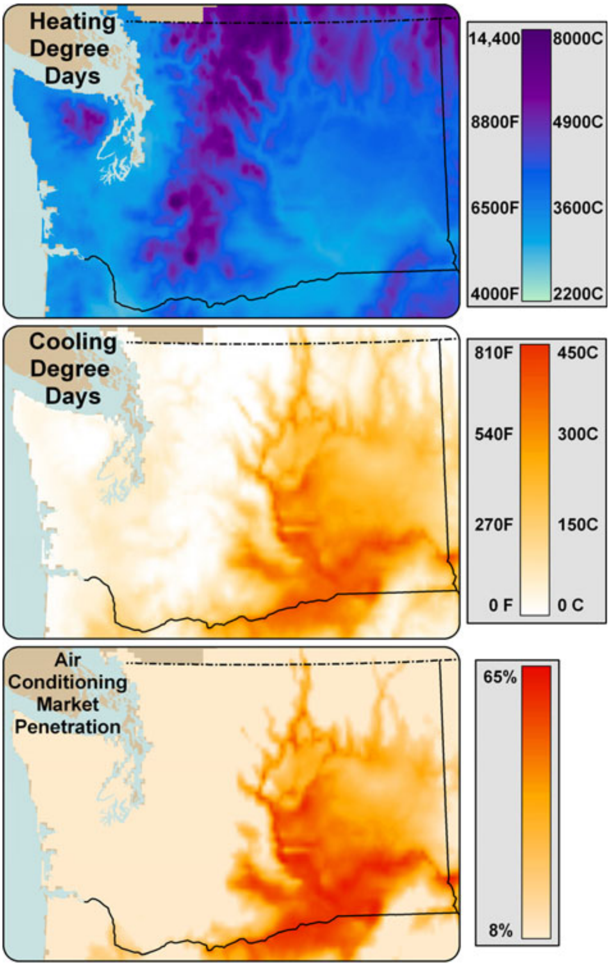


Fig. 6 Long-term average historical heating degree days (*top panel*), cooling degree days (*middle panel*), and estimated saturation air conditioning market penetration (*bottom panel*) for Washington (1970–1999). Heating degree days are in units of degree Celsius based on a threshold of 18.33°C (65°F). Cooling degree days are based on a threshold of 23.89°C (75°F). Air conditioning market penetration is expressed as a fraction (percent). Figure: Robert Norheim

Figure 10 shows the sensitivity of HEDI to population growth alone and decreasing HDD alone (fixed 2000 population) and projects the combined effects of warming and linear population growth until the end of the twentieth century for the A1B and B1 scenarios. Table 3 tabulates the values in a matrix format for different combinations of warming scenario and population growth. For HEDI, because the effects of changing population and changing climate are in opposite directions, the effects of population growth alone are associated with the greatest increases to HEDI (+38% by the 2020s), whereas the effects due to climate alone are associated with decreases to HEDI (−12% by the 2020s). The combined effects result in impacts between the two extremes in the sensitivity analysis. Changes in HEDI will affect both demand for fossil fuels for space heating and electrical power demand.

Figure 11 shows the sensitivity of CEDI to population growth alone, increasing CDD alone (fixed 2000 population and A/C penetration), and the combined effects of increasing CDD and A/C penetration (fixed 2000 population), and projects the combined effects of warming and linear population growth until the end of the

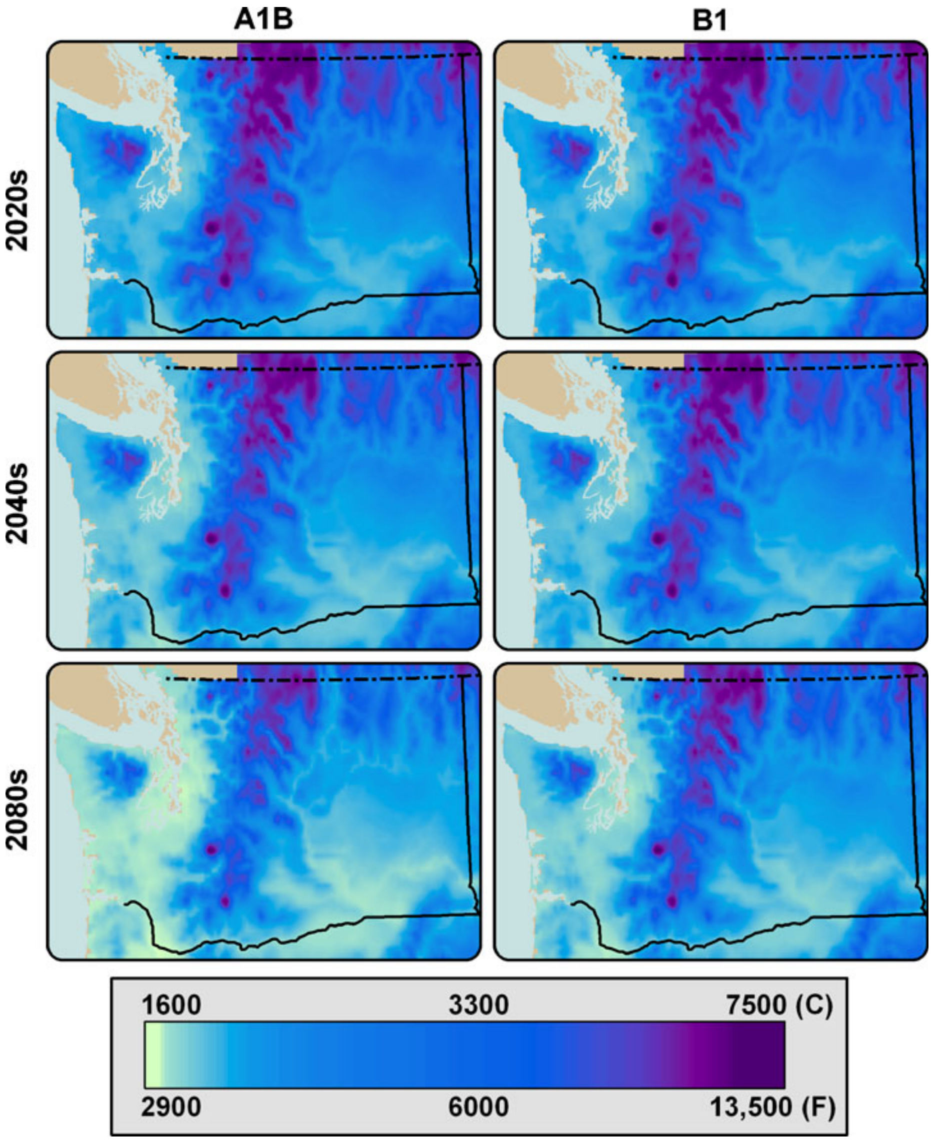


Fig. 7 Long-term average annual total heating degree days for WA, for three future time periods and two emissions scenarios. Heating degree days are in units of degrees Celsius based on a threshold of 18.33°C (65°F). Figure: Robert Norheim

twenty-first century for the A1B and B1 scenarios. Table 3 tabulates the values in a matrix format. The response of CEDI is fundamentally different from that for HEDI, because in this case the effects of increasing population, increasing CDD, and increasing use of A/C on CEDI are all in the same direction. Thus the greatest effects are shown to occur for combined effects of population growth and warming. CEDI is associated primarily with electrical energy demand for air conditioning. In

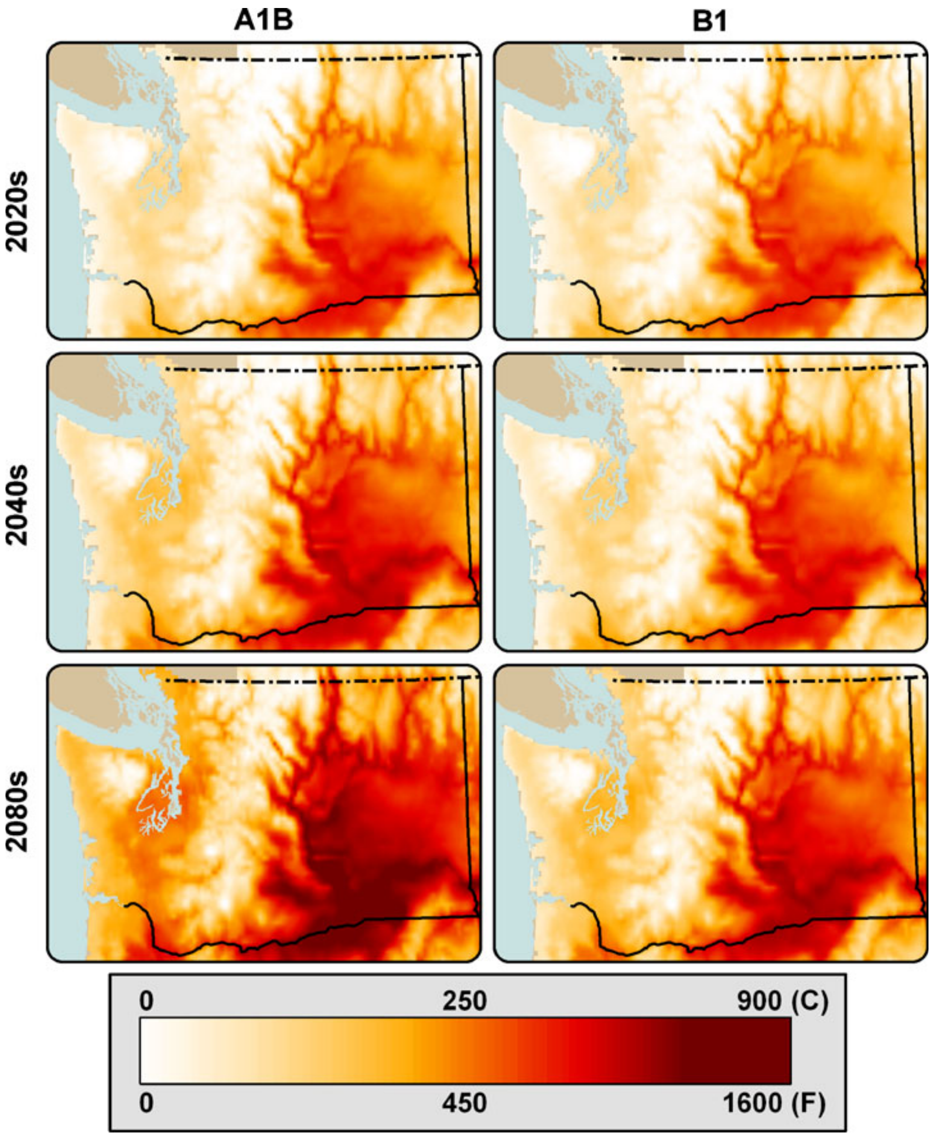


Fig. 8 Long-term average annual total cooling degree days for WA, for three future time periods and two emissions scenarios. Cooling degree days are based on a threshold of 23.89°C (75°F). Figure: Robert Norheim

the next section we will discuss the potential effects of warming on peak electrical energy demand.

As noted above, large population uncertainties at the end of the twenty-first century play an important role in determining the uncertainties in the 2080s projections of HEDI and CEDI. We explore these uncertainties by calculating HEDI and CEDI for the 2080s climate, assuming that population has stabilized at the projected 2045

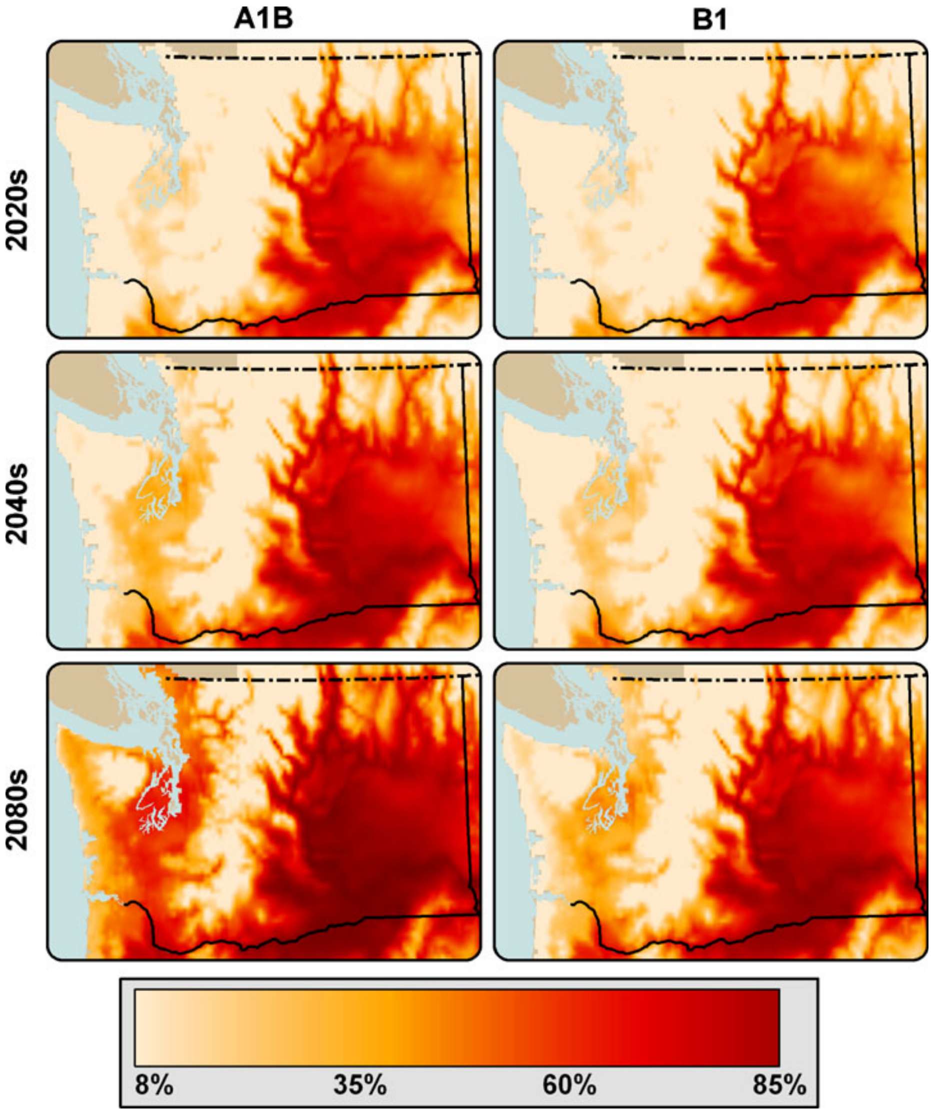


Fig. 9 Projected saturation air conditioning market penetration (expressed as a fraction) for three future time periods and two emissions scenarios. (Note that a lower bound of 0.08 has been imposed). Figure: Robert Norheim

level (Table 3). For this population growth scenario HEDI is lower in the 2080s than in the 2040s, due to stable population and decreased HDD. This shows that, depending on population growth, heating energy demand could potentially peak in mid-twenty-first century. CEDI, however, continues to strongly increase from the 2040s to the 2080s (roughly doubling) even with the assumption of a stable population, because CDD and A/C penetration continue to increase dramatically with warming.

Table 3 Matrix summary of WA State HEDI and CEDI estimates for different combinations of PNW climate (rows) and population (columns) for A1B and B1 emissions scenarios. (HEDI units: million person-HDD, CEDI units: million person-CDD)

Population	2000	2025	2045	2085
A1B scenario				
HEDI				
Climate				
1980s	3.12	4.31	5.26	7.15
2020s	2.76	3.81	4.64	6.32
2040s	2.51	3.47	4.23	5.76
2080s	2.13	2.94	3.59	4.88
CEDI				
Climate				
1980s	0.033	0.046	0.057	0.077
2020s	0.073	0.101	0.123	0.168
2040s	0.130	0.180	0.219	0.298
2080s	0.284	0.392	0.478	0.651
B1 scenario				
HEDI				
Climate				
1980s	3.12	4.31	5.26	7.15
2020s	2.78	3.84	4.68	6.37
2040s	2.64	3.65	4.45	6.05
2080s	2.38	3.28	4.00	5.45
CEDI				
Climate				
1980s	0.033	0.046	0.057	0.077
2020s	0.064	0.089	0.108	0.148
2040s	0.092	0.127	0.155	0.211
2080s	0.158	0.218	0.266	0.362

We close this section with a discussion of the relative magnitude of changing energy use associated with the changes in HEDI and CEDI. As discussed above, changes in CEDI are very large on a percent basis, but for the historical baseline and early twenty-first century the absolute magnitude of CEDI is small in comparison with HEDI. Direct comparison of energy demand associated with HEDI and CEDI is somewhat complex, because the sources of energy that supply these fundamental drivers of space heating and cooling demand, and the efficiency of end-use technology in each case is not directly comparable. Residential energy demand associated with HEDI, for example, is supplied by both fossil fuels (about 47% averaged for the 1990s, http://www.cted.wa.gov/site/533/default.aspx, 5 Jan 2009) and electric power (53%), and efficiencies of end-use technology range from about 0.75–0.98 for fuel-based systems to 1.0–3.0 for electrical heating. Energy demand associated with CEDI is supplied primarily by electrical power for air conditioning, which typically has a higher end-use coefficient of performance of 2.0–3.0.

For the purpose of discussion, we consider only residential heating and cooling load supplied by electrical power. To facilitate this comparison, HEDI is multiplied by 0.53 to account for the fraction of heating energy demand that is taken by electrical power, and end-use efficiency is assumed to be 1.0 (electrical resistance heating). CEDI is assumed to be supplied entirely by electrical power, with an end-use coefficient of performance of 2.5. Using these adjustments, Table 4 shows estimates of the percentage of total residential space heating demand supplied by

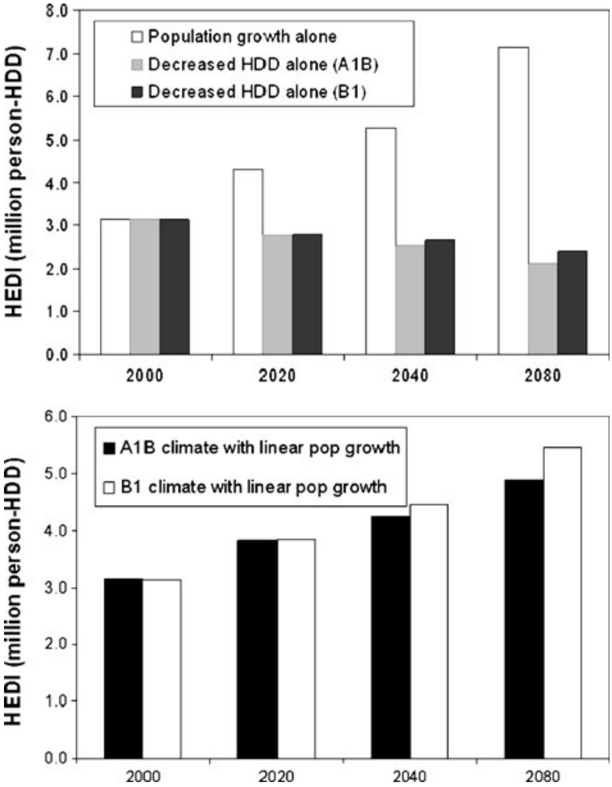


Fig. 10 The *top panel* shows sensitivity of HEDI to population growth alone, and decreasing HDD alone. The *bottom panel* shows the combined effects of population growth and decreasing HDD on HEDI for two emissions scenarios. (see Table 3 for full matrix of values)

electric power associated with heating and cooling demand, respectively. For the historical condition, cooling energy demand is estimated to account for less than 1% of total annual residential electrical demand. For the 2020s, 2040s, and 2080s, respectively, cooling energy demand accounts for 1.7–2.0%, 2.6–3.8%, and 4.8–9.1% of the total residential demand. Thus for the future scenarios, residential heating energy demand remains the dominant portion of the load, despite dramatic increases in cooling load on a percent basis.

It is important to note that impacts in summer at smaller spatial scales (e.g. affecting small PUDs in eastern WA) may be much larger than those shown for Washington as a whole. Likewise, other elements of the load mix not considered here may behave very differently than residential heating and cooling demand. Energy demands associated with cooling needs for commercial computer resources, for example, are probably negatively correlated with HEDI, and positively correlated with CEDI and are likely to have a very different sensitivity to warming. More detailed studies will be needed to assess the impacts in different sectors of the energy market and different geographic areas of the state.

3.8 Changes in peak electrical demand in summer

In the PNW, peak electrical demand in summer is currently relatively low (reflecting low values of CEDI), and the sensitivity of peak demand to warming is modest.

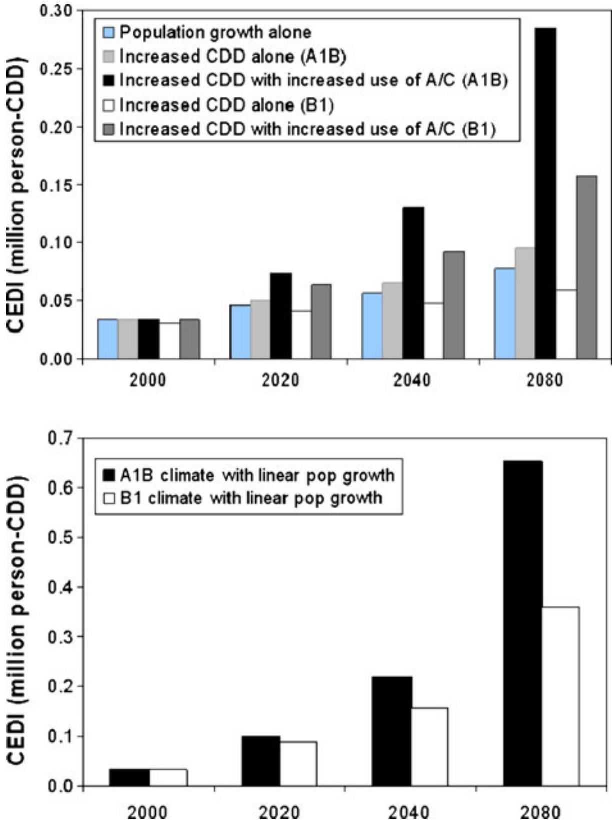


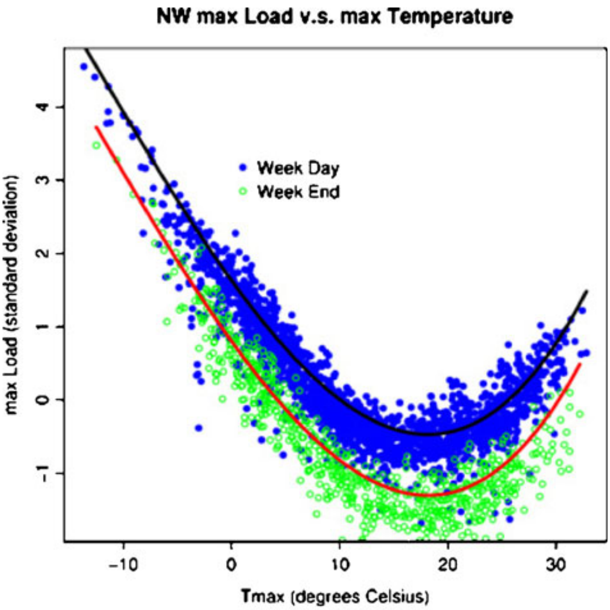
Fig. 11 The top panel shows sensitivity of CEDI to population growth alone, increasing CDD alone, and the combined effects of increasing CDD and increasing A/C penetration alone. The *bottom panel* shows the combined effects of population growth, increasing CDD, and increasing A/C penetration on CEDI for two emissions scenarios. (see Table 3 for full matrix of values)

In northern CA, by comparison, a much more substantial portion of the observed electrical demand is associated with warm temperatures in the summer, and the sensitivity to increasing temperature is larger (Voisin et al. 2006; Westerling et al. 2008).

Figure 12 shows non-linear relationships between daily *t*max and regional peak hourly electrical energy demand in the PNW and northern CA. Although the twentieth century summer climate in CA is not a perfect analogue for warmer conditions in the PNW, the differences between these relationships in the PNW and CA

Table 4 Percentage of estimated total residential electrical energy demand associated with HEDI and CEDI respectively

Scenario	A1B		B1	
	Percent of total demand associated with HEDI	Percent of total demand associated with CEDI	Percent of total demand associated with HEDI	Percent of total demand associated with CEDI
Historic	99.2	0.8	99.2	0.8
2020s	98.0	2.0	98.3	1.7
2040s	96.2	3.8	97.4	2.6
2080s	90.9	9.1	95.2	4.8



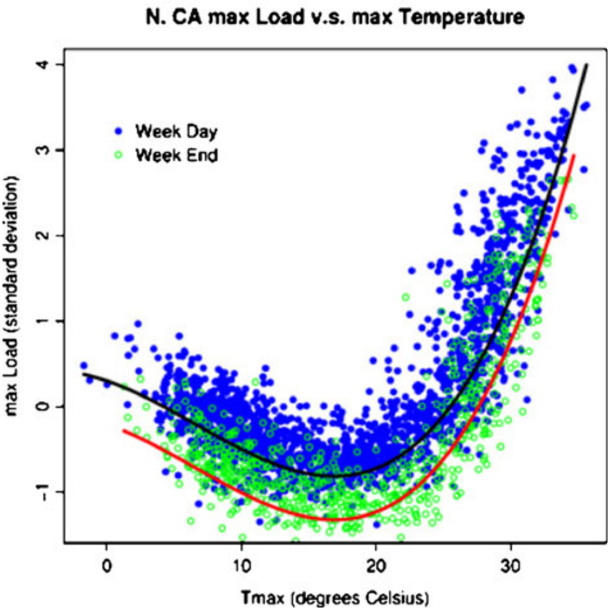


Fig. 12 Non-linear relationships between daily maximum temperature and daily peak electrical energy demand in the PNW (*top*) and northern CA (*bottom*). Source: Westerling et al. (2008)

provide important information about the kinds of changing peak electrical demand patterns that should be expected to accompany adjustments to systematically warmer conditions (such as increased use of air conditioning). Sensitivity to warmer climate is broadly interpreted as a move to the right along the x-axis in Fig. 12. Thus the slope of the fitted lines in the plots (i.e. the first partial derivative of demand with respect to temperature) characterizes the demand sensitivity to warming. Note that the slope of the fitted line is much steeper in CA than in the PNW for a given temperature. This supports the argument that changes in the PNW summer electrical energy demand will probably be much larger than would be suggested by historical patterns of use in the PNW. We note, however, that changes in *t*max could potentially be different than the projections of the daily average temperature changes we consider here. If *t*min increases strongly but *t*max does not increase appreciably, for example, peak electrical demand related to space cooling needs may be relatively insensitive to warming.

Monthly regression-based models of daily average regional scale energy demand in CA and the PNW developed by Voisin et al. (2006) also provide useful quantitative guidance on potential changes in end-use technology in the PNW in response to warming. In CA in July for example, the coefficient in the regression equation associated with population weighted temperature (i.e. the first partial derivative $\partial(\text{Demand})/\partial(\text{Temperature})$) is 53% higher than that for the PNW at the same time of year. These observed differences between the two regions support the hypothesis that increased temperatures and increased A/C market penetration will result in strongly increased sensitivity to warmer conditions on hourly time scales. These issues have been noted in earlier studies as well (e.g. NWPCC 2005), but more research is needed to understand the capacity and distribution impacts of these kinds of effects.

3.9 Future research needs

In closing this section, we list a number of specific research needs, beyond the scope of the current investigation, which have emerged in the course of preparing this paper:

1. Population projections over long time horizons (>20 years) are very uncertain and lack a credible scientific basis. New approaches and methods are needed to provide credible population forecasts on time scales that are relevant to climate change studies.
2. More detailed projections of specific impacts to daily maximum and minimum temperature are needed to facilitate better projections of daily average and peak loads at hourly time scales.
3. We have focused here on climate sensitivities related primarily to residential and light commercial space heating and cooling needs. Additional analyses estimating climate-related energy demand impacts in the larger commercial, industrial, and transportation sectors are needed to extend these results and provide a more complete picture of changes in regional energy demand.
4. The combined effects of hydrologic changes and climate change adaptation on the Columbia River hydro system are only partially understood, and more resources need to be focused on this problem. In particular, the combined effects of adaptation for hydropower production, flood control, and instream flow for fish are needed. More sophisticated tools will be needed to explore and prioritize the full range of adaptation alternatives, and to understand the implications for the transboundary relationship between Canada and the US in the Columbia River basin.
5. Linkages between water availability and conventional energy production (e.g. via power plant cooling needs) have been established in other studies, but

projections of constraints on conventional resources that incorporate altered water availability in summer are not currently available. These effects should be incorporated in estimates of warm-season energy supplies from conventional resources.

6. The potential for increased use of renewable energy (such as residential solar water heating or photovoltaic systems) should be considered in future work to estimate both supply and demand, particularly in summer when these technologies are most effective in the PNW.
7. There is a need to better understand the potential conjunctive management strategies with other western regions, and to assess the infrastructure needs associated with these strategies.
8. A quantitative assessment of the effects of glacial melt on summer low flows and late summer hydropower production is needed, particularly in the context of critical drought years.

4 Conclusions

Hydropower production in the Columbia River basin is projected to decline slightly on an annual basis by mid-twenty-first century, but is projected to increase in winter and decline in summer. By the 2020s, regional hydropower production is projected to increase by 1.0–4.5% in winter, decrease by 8.6–11.0% in summer, with annual reductions of 0.8–3.4%. By the 2040s hydropower production is projected to increase by 4.7–5.0% in winter, decrease by about 12.1–15.4% in summer, with annual reductions of 2.0–3.4%. By the 2080s hydropower production is projected to increase by 7.7–10.9% in winter, decrease by about 17.1–20.8% in summer, with annual reductions of 2.6–3.2%. The largest and most robust changes in hydropower production are projected to occur from June–Sept, during the peak air conditioning season.

Despite decreasing HDD with projected warming, heating energy demand is projected to increase due to population growth. In the absence of warming, population growth is projected to increase heating energy demand in WA by 38% by the 2020s, 68% by the 2040s, and 129% by the 2080s. For fixed 2000 population, projected warming would reduce heating energy demand by 11–12% for the 2020s, 15–19% for the 2040s, and 24–32% for the 2080s due to decreased heating degree days. Combining the effects of warming with population growth, heating energy demand for WA is projected to increase by 22–23% for the 2020s, 35–42% for the 2040s, and 56–74% for the 2080s. Increases in HEDI will have important impacts on both demand for fossil fuels such as natural gas and demand for electrical power. The experience of individual consumers and utilities to these changes in demand will be fundamentally different. Individual consumers will likely see reductions in energy use, however many utilities will face rising overall demand due to population growth.

Cooling energy demand, which is currently a relatively small component of residential energy demand, is projected to increase rapidly due to increasing population, increasing cooling degree days, and increasing air conditioning market penetration. In the absence of warming, population growth is projected to increase cooling energy demand in WA by 38% by the 2020s, 69% by the 2040s, and 131% by the 2080s. For fixed 2000 population, warming would increase cooling energy demand by 92–

118% for the 2020s, 174–289% for the 2040s, and 371–749% by the 2080s due to the combined effects of increased CDD and increased air conditioning market penetration. Combining the effects of warming with population growth, cooling energy demand would increase by 165–201% (a factor of 2.6–3.0) for the 2020s, 363–555% (a factor of 4.6–6.5) for the 2040s, and 981–1845% (a factor of 10.8–19.5) by the 2080s. Increases in CEDI are very tightly coupled to increasing electrical energy demand, because air conditioning technology is powered primarily by electricity. Although increases in CEDI are very large on a percent basis, in absolute terms the increases are relatively small in comparison with increases in HEDI. For residential heating and cooling energy demand, for example, cooling energy demand is projected to increase from less than 1% of the total electrical energy demand in the late twentieth century to about 4.8–9.1% of the total demand in the 2080s.

Taken together the changes in energy demand and regional hydropower production suggest that energy adaptation to climate change in the cool season will be easier than in the warm season. Increases in hydropower production in cool season will at least partially offset increases in HEDI. Adapting to changes in warm season energy supply and demand will be more difficult because increases in CEDI (which are also more directly coupled to electrical energy demand) will accompany systematic losses of hydropower resources in the same months. These effects in summer will put additional pressure on other sources of energy. Peak electrical loads for air conditioning are also likely to increase, creating potential capacity, distribution, or voltage stability problems.

The ability to transfer electrical energy from the PNW to other regions is likely to decrease in May, June, July, and August due to reduced hydropower supplies and increased local demand. Excess capacity in other regions (e.g. CA and the SW) in winter (due to reduced winter heating demand and increased capacity needed to cope with higher summer demand) is likely to make more capacity available to the PNW. These changes in conjunctive management opportunities will impact not only supply and capacity considerations in both regions, but also revenue projections, because power exports from the PNW to CA in summer are currently associated with high market values.

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