Energy-relevant impacts of climate change in the Pacific Northwest

a report by

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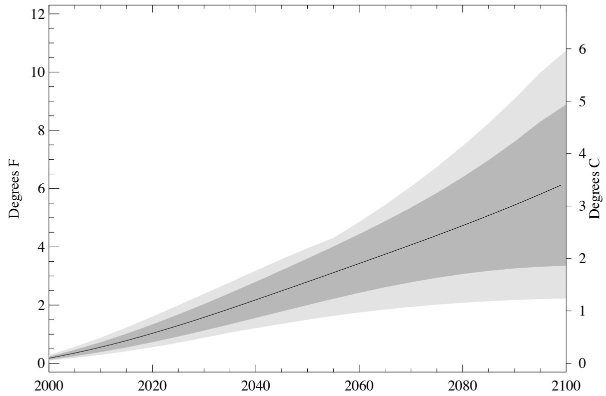
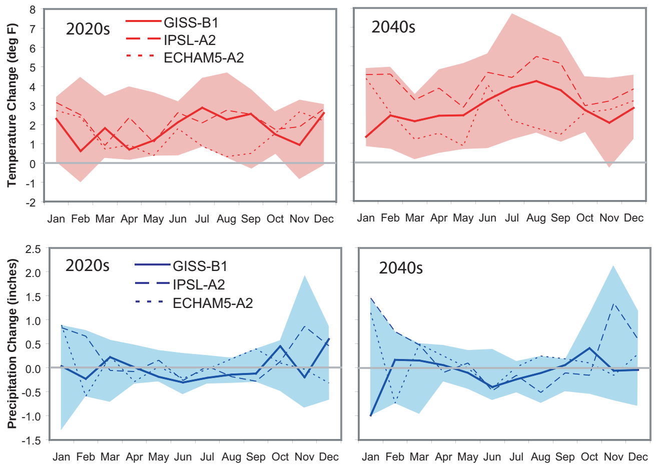


A range of warming scenarios for the Northwest from 20 simulations by global climate models. Average shown as thick line, lowest and highest shown by light gray shading, and dark gray encloses about 70% of the model results.



Changes in temperature (top) and precipitation (bottom) month by month, for all scenarios (shaded envelopes) and for three specific scenarios.

Summary.

Observations show substantial warming (1.5°F) in the Pacific Northwest, and indeed the entirety of western North America, over the past 50-100 years. Concomitant hydrologic changes toward earlier peak flow, reduced summer flow, and increased winter flow have also been observed and are several lines of evidence show that warming is responsible.

Continued warming in the region is extremely likely because greenhouse gases are rising. We have examined 20 scenarios from state-of-the-art climate models and summarize here the changes they project. The average warming rate in the Pacific Northwest during the next century is expected to be in the range 0.1-0.6°C (0.2-1.0°F) per decade, with a best estimate of 0.3°C (0.5°F) per decade.

Present-day patterns of greenhouse gas emissions constrain the rate of change of temperature for the next few decades: humans are committed to some degree of additional climate change. Beyond mid-century, the projections of warming depend increasingly on emissions in the next few decades and hence on actions that would limit or increase emissions.

Projected precipitation changes are modest, and are unlikely to be distinguishable from natural variability until late in the 21st century. Most models have winter precipitation increasing and summer precipitation decreasing. The aggregate changes in climate will likely produce continued decreases in June-September flow in most rivers in the Northwest, with increases in winter flow. However, changes in wind energy potential will probably be small.

2020s*	temperature	precipitation
low	0.4°C (0.7°F)	-4%
average	1.1°C (1.9°F)	+2%
high	1.8°C (3.2°F)	+6%

2040s*	temperature	precipitation
low	0.8°C (1.4°F)	-4%
average	1.6°C (2.9°F)	+2%
high	2.6°C (4.6°F)	+9%

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* In this document, “2020s” means the 2010-2040 average minus the 1970-2000 average, similarly for 2040s and 2080s.

1. Introduction: global and Northwest climate change

Weather and climate affect different economic sectors in different ways, but in the Northwest, the importance of hydropower plays a special role in connecting the energy industry with climate. For this reason, and because the energy industry is technically and analytically advanced, for example in the capabilities for quantitative risk assessment, many energy companies are asking important questions about climate change.

This report arose because Portland General Electric asked such questions. In particular, PGE asked the Climate Impacts Group (CIG) at the University of Washington to provide the latest, most defensible scenarios of future climate change in the Northwest, and to describe how it would change the hydropower and wind generation capabilities upon which PGE relies for a portion of its generating capacity.

1a. Global climate change

The air in Earth's atmosphere includes certain "greenhouse gases", e.g., water vapor, carbon dioxide, and methane, which, by preventing infrared energy from escaping to space, keep the planet warm and habitable. Without them, Earth's average temperature would be well below 0°F. Human activities like the burning of "fossil" fuels – coal, oil, and natural gas – raised concentrations of these gases substantially over the past 150 years (mostly during the last 30 years), to values not seen in millions of years (Prentice et al. 2001).

The "greenhouse effect" refers to a natural process in which certain gases (water vapor, carbon dioxide, and methane are the most important) allow the sun's radiant energy to pass through the atmosphere, but absorb the radiant energy that Earth emits at lower wavelengths. This leads to a natural warming of the Earth. Fluctuations in the composition of the Earth's atmosphere on geologic timescales have produced vastly different climates – 100 million years ago, Earth was so much warmer that alligators lived in what is now Siberia, and the carbon dioxide content of the atmosphere was probably 4 to 8 times present levels (Kump et al., 1999; Prentice et al., 2001). Throughout Earth's history, the natural warming of the greenhouse effect has kept the planet warm enough to sustain life. What is unusual now, however, is the rate at which CO_2 and other greenhouse gases are now increasing.

In the last 150 years or so, humans have enhanced the natural greenhouse effect by increasing the quantities of key greenhouse gases. Carbon dioxide has increased 36% because of burning fossil fuels and reducing forested area, and methane has increased by 151% through agriculture (chiefly cattle and rice paddies) and other human sources (Prentice et al., 2001). Other greenhouse gases have also increased, including some (CF_4, C_2F_6, and SF_6) whose human sources exceed natural sources by a factor of 1,000 or more, and some (e.g., the chlorofluorocarbons) that have no natural sources at all (Prather et al., 2001). In the global mean, carbon dioxide accounts for 60% of the radiative forcing by greenhouse gases, and methane 20% (Ramaswamy et al., 2001). Water vapor is also a greenhouse gas, but its influence is considered a response (positive feedback) of the climate system rather than as a separate forcing.

Two key questions arise from the increase in greenhouse gases: (1) is the planet warming? and (2) can we rule out natural causes for recent climate change? These two questions are answered in this section, drawing heavily on the assessment reports by the "Intergovernmental Panel on Climate Change", or IPCC. The IPCC was created in 1988 and has issued major reports in 1990, 1996, and 2001 (the First, Second, and Third Assessment Reports). Much of what is presented in this section comes from the first volume of the IPCC's Third Assessment Report (TAR). This comprehensive report (884 pages) was written by over 650 scientists who volunteered considerable time over a period of three years to write the report, and was reviewed by 300 additional scientists (IPCC, 2001). The IPCC assessments constitute the most comprehensive, authoritative statement about the state of the science of climate change. The interested reader is strongly urged to consult the IPCC "Summary for Policymakers" (see references).

The IPCC answered affirmatively to both of the questions posed in the previous paragraph.

In answering yes to the first question, whether Earth is warming, the IPCC stated that "An increasing body of observations gives a collective picture of a warming world and other changes in the climate system." Evidence marshalled included the following:

- global average surface temperature has increased by 0.6°±0.2°C during the 20th century;
- Northern Hemisphere snow cover has decreased by about 10% since the late 1960s;
- most mountain glaciers retreated during the 20th century;
- sea ice extent and thickness have decreased since the 1950s; and
- in addition (Cayan et al., 2001), since about 1950 the timing of spring, as marked by blooming or leafing-out dates of various plants, has advanced in much of North America.

Urbanization (the growth of cities around weather stations), though a factor at some locations, has barely affected the estimation of global average temperatures (Peterson, 2003). Additional evidence that Earth's surface is warming has accumulated since the IPCC TAR, including, thinning and contraction of Arctic sea ice, disintegration of Antarctic ice shelves, earlier spring melt on lakes and rivers, earlier snowmelt runoff in the West (Stewart et al. 2005), poleward movement of numerous species, earlier bloom dates of various flowering plants, warming of the ocean's interior in a pattern consistent with the pattern of atmospheric warming (Barnett et al. 2005). Although a few carefully selected observations might show a contrary pattern, the vast weight of evidence clearly points toward a warming world.

What about satellite records that supposedly show no warming? The satellite records have several difficulties, with which climate researchers have been grappling. First, these satellites measure the temperature not of the (unquestionably warming) surface, but of a thick layer of the atmosphere. Second, the satellite record, which began only in 1979, consists not of a single well-calibrated satellite but a patched-together history of nine different satellites. In order to account for inter-satellite differences and other effects like orbital changes and the cooling of the stratosphere, scientists have had to apply various complicated corrections and different groups use different approaches. When most groups apply such corrections, they find a trend 1979-2003 of 0.1-0.2 K/decade; the surface warming is 0.17 K/decade (e.g., Fu et al., 2004).

The warming in the 20th century did not proceed smoothly, but rather in two stages: one from 1910 to 1945 and one since 1976, with temperatures relatively constant at other times. This fact prompts a crucial question: was the warming natural or man-made?

Natural causes of climate change include solar variations, volcanic eruptions, and the redistribution of heat by the oceans. In answering this more complicated question about the cause of warming, scientists have taken different approaches. One approach is to examine past climate and determine whether the warming of the late 20th century is unusual. Scientists have carefully reconstructed temperatures in the Northern Hemisphere back to A.D. 1000 (Mann et al., 2003) from tree rings and corals and other "proxy" data, and two things about recent climate stand out: (1) the 20th century warming appears to be the largest of the millennium and (2) the 1990's are likely the warmest decade of the millennium.

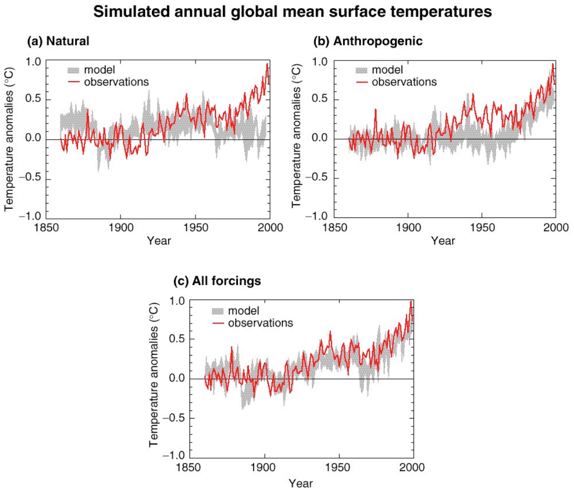

Figure 1. Global average temperature as observed (red) and as simulated using a climate model that was run with (a) natural (solar, volcanic) forcings; (b) anthropogenic (greenhouse gas, sulfate aerosol) forcings; and (c) all forcings. The results clearly show human cause for the warming of the last 40 years, and the remarkable agreement between observations and model in panel c underscores the value and complexity of climate models. From IPCC (2001), used by permission.

The second approach (Mitchell et al., 2001) is to simulate global temperatures (**Figure 1**) with a climate model while introducing various forcings, typically solar variations, volcanic eruptions, and human contributions (greenhouse gases and aerosols). When forced by natural causes alone (Figure 1a), climate models can generally reproduce the warming from 1910 to 1945, but they cannot reproduce the warming since the mid-1970's. In fact, satellite observations of solar output since 1979 show some variability associated with the 11-year solar cycle: a fluctuation of 0.1%, mostly in ultraviolet light absorbed by ozone in the stratosphere. Only when the increase in greenhouse gas concentrations is included (Figure 1b, 1c) can the models reproduce the late-20th century warming. That human influence on climate would emerge later in the century is consistent with the observation that CO_2 and most other greenhouse gases have risen far more in the last 40 years than in the previous 100 years (Prentice et al., 2001; Prather et al., 2001).

A third approach (Mitchell et al., 2001, and references therein) is to compare the spatial pattern of warming as observed and as simulated by climate models with the observed increase of greenhouse gases. The pattern early in the century does not resemble the pattern expected from increasing greenhouse gases, and hence was probably natural. By contrast, the pattern of warming late in the century does resemble the pattern expected from increasing greenhouse gases. This underscores the difference between the (probably natural) early-century warming and the (probably unnatural) late-century warming. Taken together, these pieces of evidence support the view that "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

1b. Regional climate change

At nearly all stations in the Northwest, the temperature trends (**Figure 2**) have been positive over the 1930 to 2005 period of record (the same is true for other starting years: Mote, 2003b). Most trends are between 0.1° and 0.4°F per decade and minimum temperatures rose faster than maximum temperatures. Consistent with the global importance of rising greenhouse gases, there is little systematic difference between trends in urban areas and trends in rural areas (see also Peterson 2003). Warming rates are substantially larger when calculated since 1960, consistent with global results.

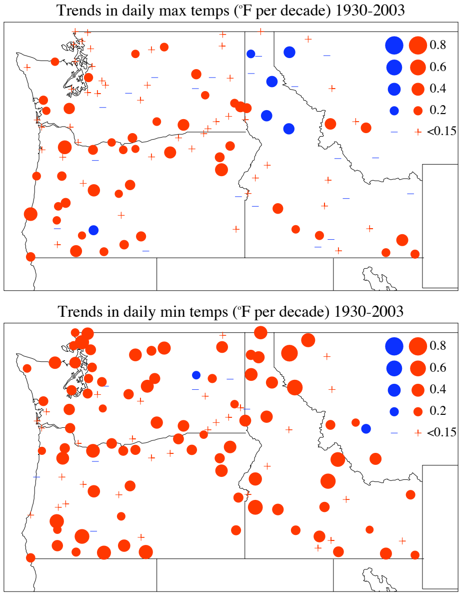

Figure 2. Linear trends in annually averaged daily maximum (top) and minimum (bottom) temperature. Red circles indicate positive trends, blue circles negative trends.

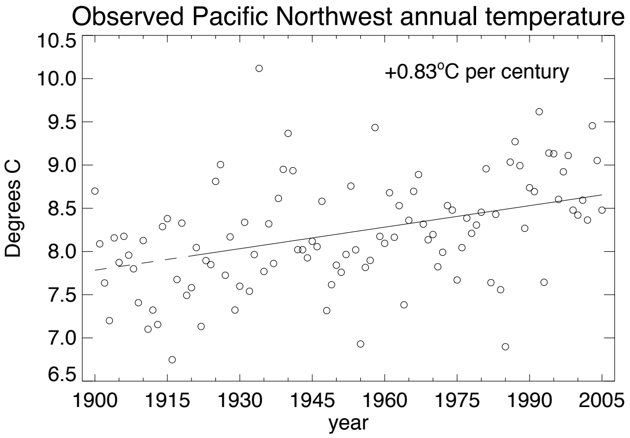

Figure 3. Regionally averaged temperature with linear trend for the 1920-2005 period (extrapolated back, dashed line).

Combining the stations into climate divisions and then area-weighting them to form a regional average (as in Mote et al. 1999, updated) produces a regionally averaged time series of temperature (**Figure 3**). The warmest single year was 1934, but the warmest 5, 10, and 20 years of the record are the last 5, 10, and 20 years. The regional warming trend of 0.83°C over the 20th century slightly exceeds the global average (0.6°C) but is about the same as the global land average.

Precipitation trends depend more on the period chosen for analysis (**Figure 4**) than do temperature trends. Indeed, a straight-line fit is a poor way to characterize precipitation variability. Part of the variability in precipitation is related to fluctuations in the atmosphere and ocean in the Pacific Basin, including El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), which partly explains the slight decline in precipitation in the past 50 years.

What role, if any, did rising greenhouse gases play in 20th century warming in the Northwest? The original pattern-detection studies (see section 1a) attributed causes of temperature trends on the scale of continents, but recent work (Karoly and Wu 2005) indicates that the signal of human influence on climate is now detectable on the scale of the Northwest. However, for precipitation, no anthropogenic signal has yet emerged even on the global scale (Gillett et al. 2004).

Hydrologically important consequences of regional warming have already emerged in the Northwest. During the past 50 years, peak streamflow in unregulated snowmelt-dominated basins has shifted earlier by 1-3 weeks, winter flow has increased and summer flow has decreased (Stewart et al. 2005). Spring snowpack has declined by about 35% (Mote 2003a, Mote et al. 2005a, Hamlet et al. 2005).

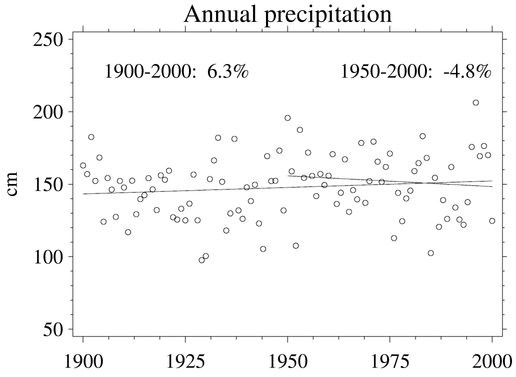

Figure 4. Regionally averaged precipitation with linear trends calculated separately for the periods indicated.

2. Global climate models

Over the decades, more than 20 research centers around the world have developed and used very sophisticated simulation models of the global climate. These models typically resolve the atmosphere with between 6,000 and 15,000 grid squares horizontally, with about 20 atmospheric layers. By calculating energy fluxes between the sun, atmosphere, and surface, they compute surface temperature distributions that compare surprisingly well with observations. In the past 6-8 years climate models have used increasingly sophisticated representations of the ocean, land surface, and sea ice.

As part of the global effort to quantify past and future changes in climate, these research centers have performed a coordinated set of experiments using different scenarios of change in greenhouse gas and in sulfate aerosols (which promote cloud formation in certain regions and hence partly offset greenhouse warming). These new scenarios have been provided as part of the assessment efforts of the Intergovernmental Panel on Climate Change (IPCC), which is in the process of producing a major assessment report due out in early 2007. We chose to use two scenarios, A2 and B1, that lie near the upper and lower limits of future greenhouse gas changes especially beyond 2050 (**Figure 5**). The climate forcing of all scenarios is similar until mid-century.

For this study, we chose a total of ten climate models that had each performed simulations of the A2 (yellow) and B1 (green) scenarios as well as simulations of the 20th century using observed changes in greenhouse gases and sulfate aerosols. We evaluated the models' global climate sensitivity (reported below in this section) and their ability in the 20th century simulations to reproduce observed seasonal variations in Northwest climate (reported in section 2 below). Model output was obtained from https://esg.llnl.gov:8443/index.jsp as monthly values, and analyzed at the University of Washington by the authors of this report.

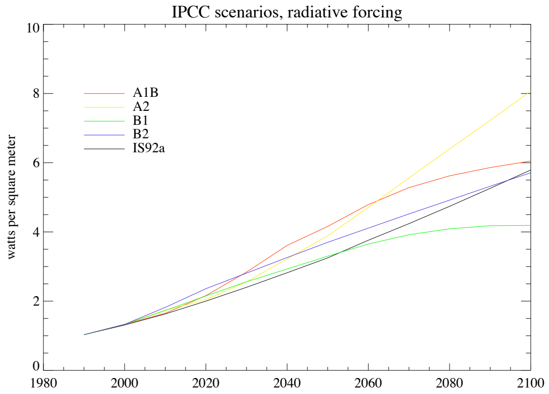

Figure 5. Radiative effects of rising greenhouse gases using several scenarios of socioeconomic change. In this report we use A2 and B1.

The new set of models has not been extensively evaluated and compared by the climate science community, and in particular, the models' global sensitivity to greenhouse gas increases has not been calculated. Formerly, this was calculated either as the "equilibrium climate sensitivity" or the "transient climate response" (TCR). The climate sensitivity is defined as the equilibrium temperature change in a simulation with a doubling of carbon dioxide; because the climate system takes a long time to come into equilibrium, the calculation of the effective climate sensitivity was typically performed only in models with a very simple ocean component, which was standard before the mid-1990s. By the late 1990s most models included a sophisticated ocean, and the TCR was a more economical metric of models' sensitivity. The TCR is defined as the global mean temperature change at the time of CO2 doubling in a simulation in which the CO2 increased at 1%/year (roughly IS92a, the black curve in Figure 5). The range of values of TCR reported in IPCC 2001 was 1.1-3.1°C (their Table 9.1).

The new IPCC model simulations included a 1%/year scenario, and we could have obtained those simulations and calculated a TCR since no one else seems to have done so. However, those runs were not otherwise of interest to us, so instead we calculated the rate of warming (globally averaged temperature increase) in each model's A2 scenario as a linear fit during the 2000-2050 period, and compared these to the TCR values reported in IPCC 2001 (Table 1). This method

model	TCR-A2 (2005)	TCR (2001)
PCM1	0.80	1.27
GISS-ER	1.06	1.45
CSIRO-MK3	0.86	2.00
CGCM3.1	1.35	1.96
CCSM3	1.36	1.58
HadCM3	1.36	2.00
CNRM_CM3	1.07	--
MIROC_3.2	1.37	--
IPSL_CM4	1.22	1.96
ECHAM5	1.21	1.4

Table 1. Estimated TCR from the A2 simulations (°C) and reported by IPCC 2001 for each model's predecessor. In some cases the 2005 version of the model is substantially different and not comparable; models indicated by -- had no predecessor represented in IPCC (2001). Lower TCR reflects the method, not lower model sensitivity.

produces lower values than the true TCR. As we shall see, there is only a loose relationship between the rate of warming globally and the rate of warming in the Northwest. Judging from our analysis and comparing with TCR, the models chosen for our analysis are neither the most nor the least sensitive on the global scale.

3. Model evaluation: 20th century climate of the Northwest.

For this study the Pacific Northwest is defined as the region between 124° and 111° west longitude, 42° to 49° north latitude: Washington, Oregon, Idaho, and western Montana. Models have different resolutions, but the number of model grid points enclosed in this latitude-longitude box is typically 12-20. We simply average the temperature and precipitation values at all the Northwest grid points to define a regionally averaged time series. The reason for such averaging is that variations in model climate on scales smaller than a few hundred km is small and not very meaningful. Put another way, the models represent the variations of climate that would be the case on a fairly smooth planet with similar land-sea distributions and large smooth bumps where Earth has major mountain ranges.

Another consideration in comparing global models with observations is that there are different ways to calculate "observed" regionally averaged temperature and precipitation. A common approach is to average weather station data into "climate divisions" and combine the climate divisions into a state or regional average with area weighting ("PNW OBS"). The drawback of this approach is that it takes no account of the contribution to a regional average of high terrain, which has very few weather stations. A better estimate interpolates (horizontally) and extrapolates (vertically) observations to a uniform, high-resolution grid. Such an estimate, however, would be unsuitable for comparing with climate model output, which lacks the vertical relief. A third approach is to assimilate observed data into a weather prediction model at the spatial resolution typical of climate models; this has been done as part of the NCEP/NCAR reanalysis ("NCEP"). Both climate division and NCEP data are used for comparison with models in Figures 6-8, and there are large differences between the two "observed" averages (Figures 7-8). A quantitative evaluation of the relative merits of the various estimates of "observed" climate is beyond the scope of this paper but worth pursuing.

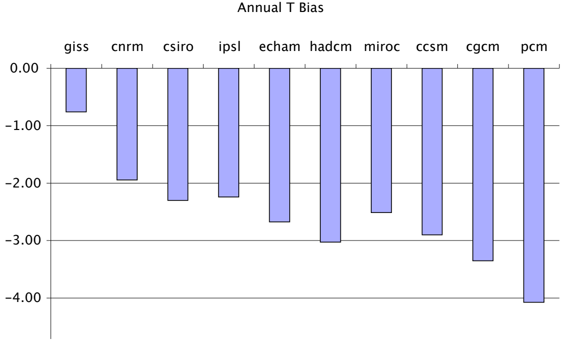

Figure 6. Difference (°C) between each model's mean annual temperature and observed temperature for the Pacific Northwest, for 1970-99 using climate division data.

The models' simulations of Northwest temperatures are uniformly too cold (**Figure 6**) and this largely determines the root-mean-square (rms) error of their seasonal cycle, which is how they are ranked in Figure 6-7. The rms error of the seasonal cycle in precipitation (**Figure 7**) shows that 8 of the models have similar errors and two are much worse than the others, owing to their very wet winter climate (Figure 8).

As shown in **Figure 8**, the models represent the gross features of the Northwest's mean seasonal cycle, including the dry winters and wet

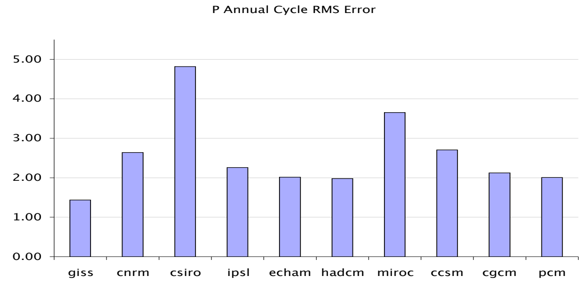

Figure 7. Each model's rms error in mean monthly precipitation. Order of models is the same as in Fig. 6.

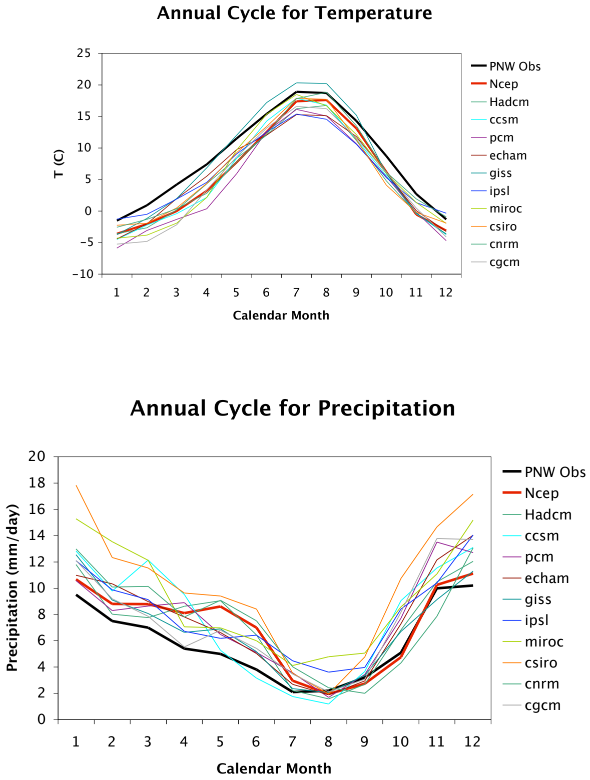

Figure 8. Mean seasonal cycle for each climate model from its 20th century simulation, compared with observations estimated from climate division data (black) and the NCEP/NCAR reanalysis (red).

summers and the magnitude of the annual cycle (though as noted the models are uniformly a bit too cold). Note also the difference between the two "observed" datasets, especially in springtime precipitation.

Another facet of 20th century climate that can be evaluated is the trend in temperature. For the global average, many models simulate a warming rate similar to the 0.8°C warming observed in the 20th century (**Figure 9**). At the regional scale, the warming rate could be dominated by changes in atmospheric circulation rather than greenhouse forcing; nonetheless, six of the models simulate a warming for the Northwest in the neighborhood of the observed warming of 0.8°C during the 20th century. We do not perform the same comparison for precipitation since there is no evidence for a response of global precipitation to greenhouse forcing.

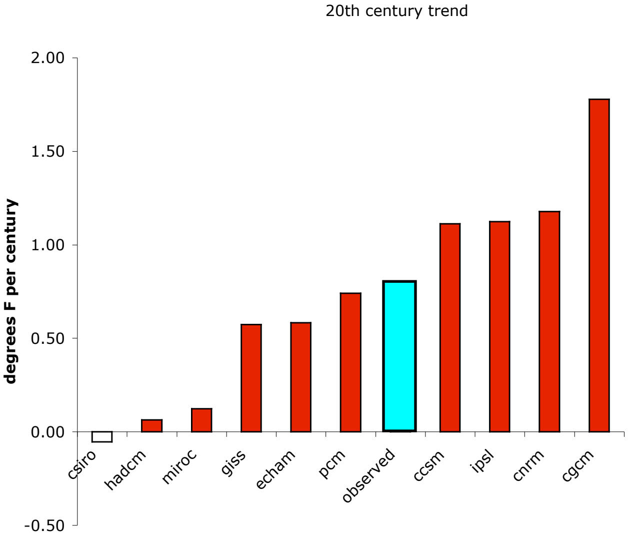

Figure 9. Each model's linear trend in annually averaged temperature for the 20th century, and the observed trend (blue).

4. 21st century trends in the annual mean

The annually averaged, regionally averaged temperature for all 20 simulations is shown in **Figure 10**, along with smooth curves. Curve fitting is accomplished by regressing each model's annual temperature data on the logarithm of the atmospheric concentration of CO2, an approximation of global radiative forcing (see Figure 1). This approach highlights the region's response to the forcing on century timescales, masking model interdecadal variability which, while interesting, can confound the forced change, especially for precipitation. Note how different the evolution of temperature is after about 2050 for the two socioeconomic scenarios, owing to the markedly different radiative forcing. Note also the different warming rates in the 20th century.

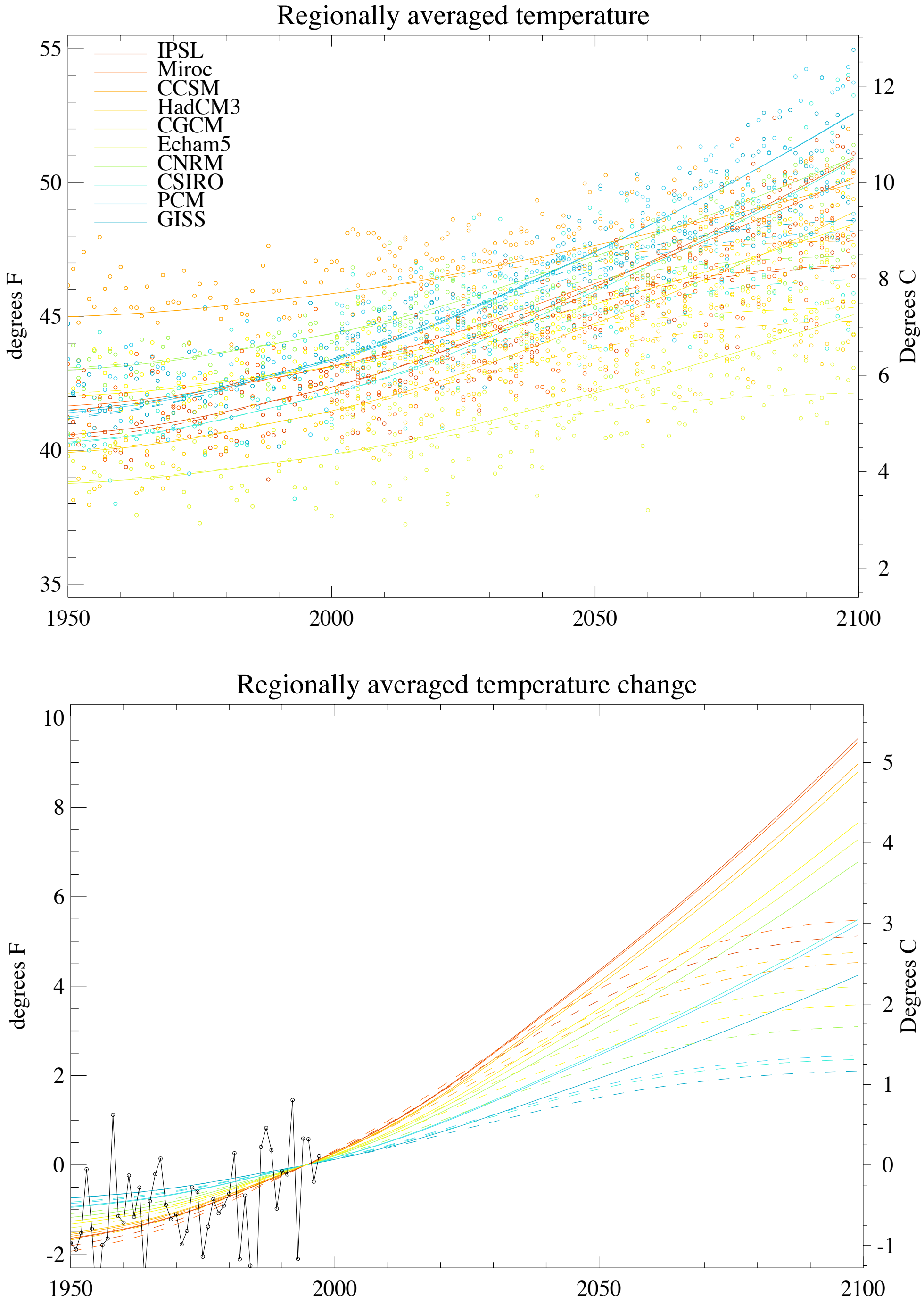

Figure 10. In the top panel, each symbol represents one year's temperature in one simulation. Smooth curves are drawn for each simulation; A2 scenarios are solid, B1 dashed. Models are color-coded according to their warming rate in the A2 scenario. In the bottom panel, the smooth curves from the top panel are replotted after subtracting the mean for the 1990s, along with observed annual temperatures (black). This forms the basis for the summary Figure on page 1.

For temperature, the observed trend has already been substantial compared with the interannual variability. On the other hand, for precipitation, the fluctuations in the past overshadow the trends predicted by all but the wettest scenarios in the future (**Figure 11**). Changes in precipitation are mostly rather small in the models, except for the CSIRO, IPSL, and CGCM scenarios in the A2 scenario in the late 21st century.

Another way to view the scenarios is to plot the change in temperature on one axis and the change in precipitation on another axis (**Figure 12**). Models clearly fall into a few clumps: a large clump around the multi-model mean change of 1.7°C and 2% precipitation increase, a second clump with very large increases in precipitation, and a third with decreases in precipitation. Unlike the situation in the global mean, where the precipitation change and temperature change of models tend to be correlated, there seems to be no correspondence between temperature change and precipitation change in the Northwest.

Other aspects of Northwest climate may change as well. For example, Meehl and Tibaldi (2004) showed projected changes in heat waves (defined as the warmest 3-day average minimum temperature) for North America, and the Northwest had relatively moderate increases (about 2°C in 100 years) compared with much of the country. However, in the same simulation (Meehl et al. 2005), the Northwest had the largest decrease in the number of frost days (40-50) in the country **(Figure 13)**. In section 6 we discuss changes in the climatology of wind as it pertains to the wind industry.

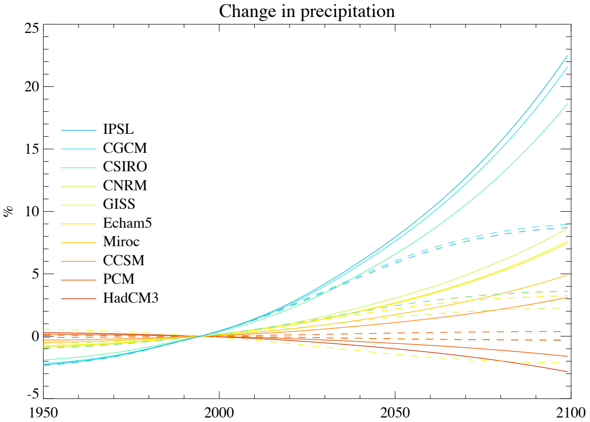

Figure 11. Smoothed precipitation traces for the 20 model simulations are shown as in Figure 6b. For preparing the summary table shown on page 1, 30-year averages were used, and the answers are substantially similar. Models are ranked from driest (red) to wettest (blue).

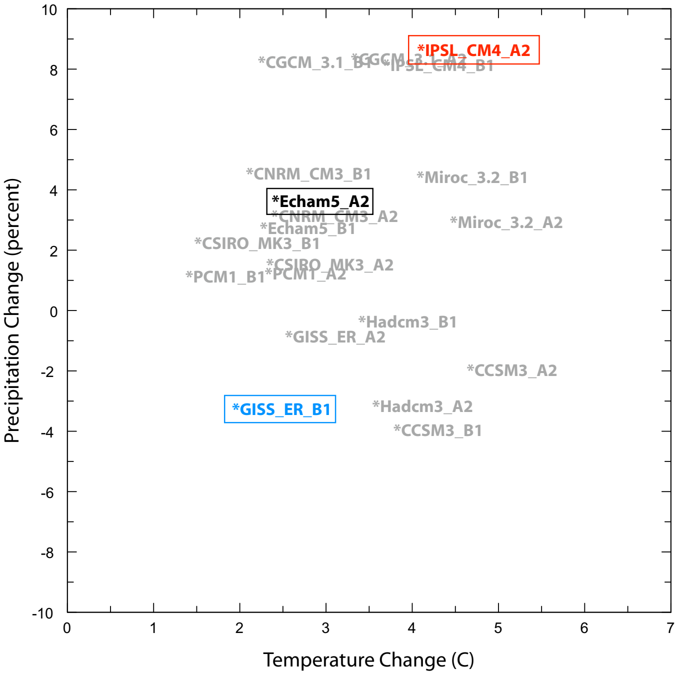

Figure 12. Scatterplot of change in annually averaged temperature and precipitation for each of the 20 scenarios, for the "2040s" (i.e., 2030-2059 minus 1970-99). Three suggested "marker" scenarios are highlighted.

5. Seasonality of changes in climate

For a fuller picture of how climate may change in the Northwest, we present also the changes in the mean annual cycle of temperature and precipitation (**Figure 14**). In most of these model simulations for both 2020s and 2040s, the increases in temperature are largest in summer (June-August).

Three of the models -- HadCM3, CNRM, and GISS -- produce substantially more (at least twice as much) warming in summer than in winter, and all but PCM and CGCM have greater warming in summer than in winter. This result stands in contrast to the common result that winter warming exceeds summer warming, and may result from soil moisture feedbacks. It has worrisome implications for water demand, agriculture, and forest fires, and will affect electricity demand.

Precipitation changes are largest in winter (December-February), and tend to be positive. In summer, precipitation declines slightly in most scenarios.

6. Relevance for the energy industry

Climate changes are likely to affect the energy industry in several ways. First, the winter warming is likely to reduce energy demand for heating in winter and increase demand for cooling in summer. With relatively low use of air conditioning in the Northwest, however, it is not clear whether increases in summer cooling demand will offset the reductions in winter heating demand.

Second, the changes in streamflow, especially on the Columbia, will substantially change the seasonal shape of hydroelectricity supply (**Figure 15,** Hamlet and Lettenmaier, 1999). Summer production will decline and winter production will increase. Firm energy reliability is unlikely to change much, unlike nonfirm energy (ibid.), but an important additional point to consider is the effects that changing streamflow will have on other uses of water, primarily summer-dependent uses like irrigated agriculture, municipal and industrial, recreational, and instream flows (Payne et al. 2004). Largest changes in flow have been observed (Regonda et al., 2005; Hamlet et al. 2005) in basins whose mean temperature is near freezing. Were the reservoir management system changed, especially with respect to flood control, advances in seasonal streamflow forecasting could net an increase of $150 million/year in aggregate for Northwest hydropower without compromising other resource objectives (Hamlet et al. 2002).

PGE expressed interest in knowing about changes in flow on the Clackamas and Deschutes Rivers in Oregon. The Climate Impacts Group has

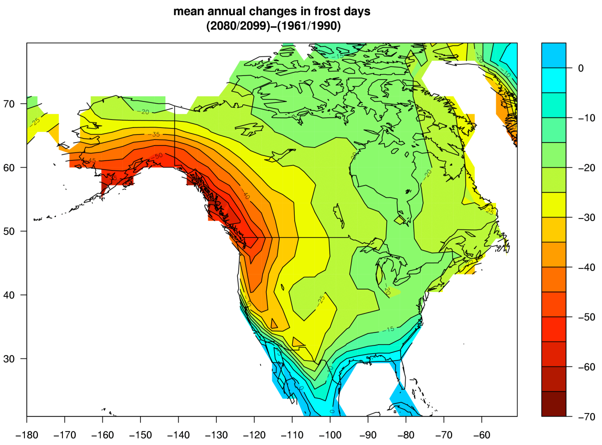

Figure 13. Changes in the number of frost days per year. From Meehl et al. (2004).

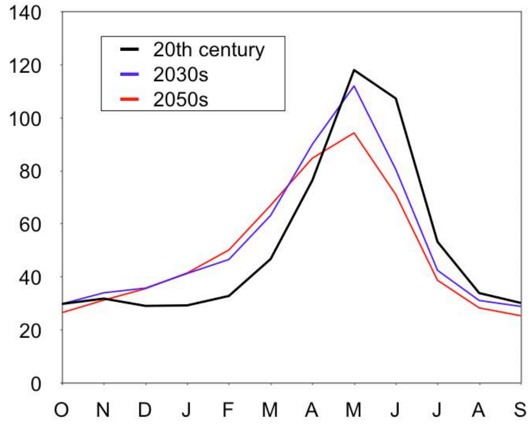

Figure 15. Simulated flow of the Snake River at Ice Harbor for 1950-2000 (black) and for future decades under warming scenarios.

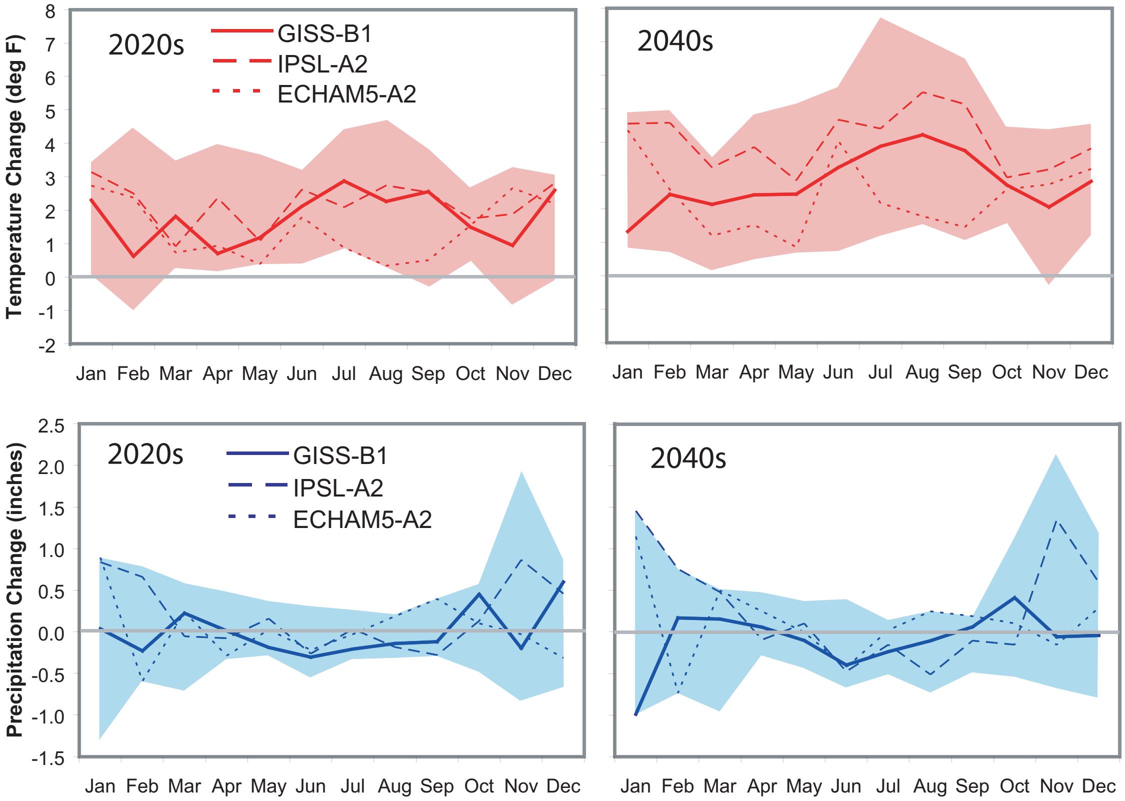

Figure 14. Changes in temperature (top) and precipitation (bottom) month by month, for all scenarios (shaded envelopes) and for the three marker scenarios.

performed simulations of the hydrology of the Northwest and has extracted streamflow at numerous locations in the Northwest, including the Deschutes (**Figure 16).** Simulating the flow on the Deshutes is fraught with difficulties owing to the substantial contribution of groundwater through the porous bedrock in the upper basin (O'Connor and Grant, 2003), so its sensitivity to warming might be less than shown in Figure 16.

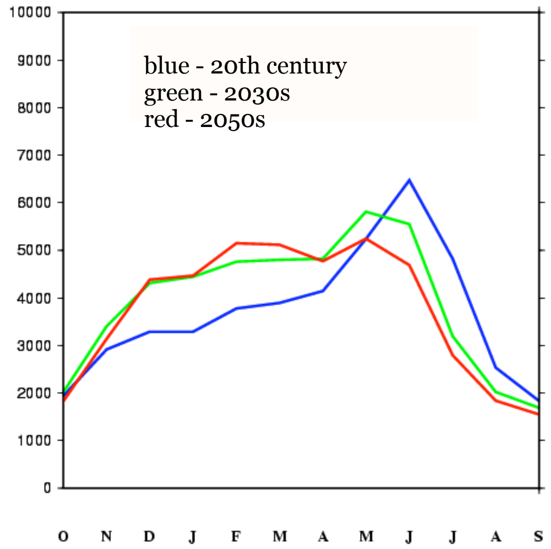

Figure 16. As in Figure 15 but for the Deschutes River at Pelton Dam.

The distributed hydrologic model, VIC (for "variable infiltration capacity"), which was used to produce the results in Figures 15 and 16, has a spatial resolution of roughly 10 km by 12 km, too coarse to accurately represent flow in a small river basin like the Clackamas. However, the University of Washington's hydrology group (part of the Climate Impacts Group) has a second distributed model, the DHSVM, which is suitable for smaller river basins and has been run for the adjacent Bull Run watershed in a study for the Portland Water Bureau (Palmer and Hahn 2002). Though primarily rain-dominated, the Bull Run has a small contribution to flow from spring snowmelt, which disappears entirely with a small amount of warming. To be more quantitative for the Clackamas would require running the DHSVM for the Clackamas.

A third potential vulnerability of the energy industry to climate change is in wind energy production. PGE has specifically asked about changes in the wind intensity at three locations: (45.6°N, 120.2°W), (45.6°N, 120.6°W), and (46.0°N, 118.7°W). Questions about the effect of climate change on winds at such fine spatial scales are best answered through the use of a mesoscale climate model to "dynamically" downscale the global climate model simulation. We have recently implemented a regional climate model based on the MM5 mesoscale modeling system and have applied this model for dynamical downscaling of global climate model output. Nested 135, 45, and 15km grids are used to downscale from climate model resolutions of approximately 150-300km. The inner, 15-km grid covers the study area including the states of Washington, Oregon, and Idaho. Among other features, the model includes detailed topographic and land-use information, which is important for simulating winds at the required spatial scale.

We present here wind results from the PCM global climate model simulation for the 1990s, 2020s, and 2050s dynamically downscaled using this MM5 modeling system. The 21st Century simulations are based on the A2 emissions scenario. The warming response for the Pacific Northwest for this simulation is in the middle of the range of models considered (**Fig 12**). We extracted the 6-hourly maximum sustained wind speed from the MM5 simulation and interpolated from the 15-km model grid to the three stations listed above. The resulting station time series were used to form cumulative distribution functions of the winds to illustrate the probability distribution of wind speeds for each decade.

For most seasons, the changes are negligible, but for the December-January-February season there is a slight (5-10%) decline in the moderate wind speeds (**Figures 17-19**); these changes are so small we do not place significant confidence in their being a robust response to global warming. The possible changes in wind energy have not been as thoroughly studied as changes in hydropower, but, in our judgment, wind power is not likely to be significantly vulnerable to climate change.

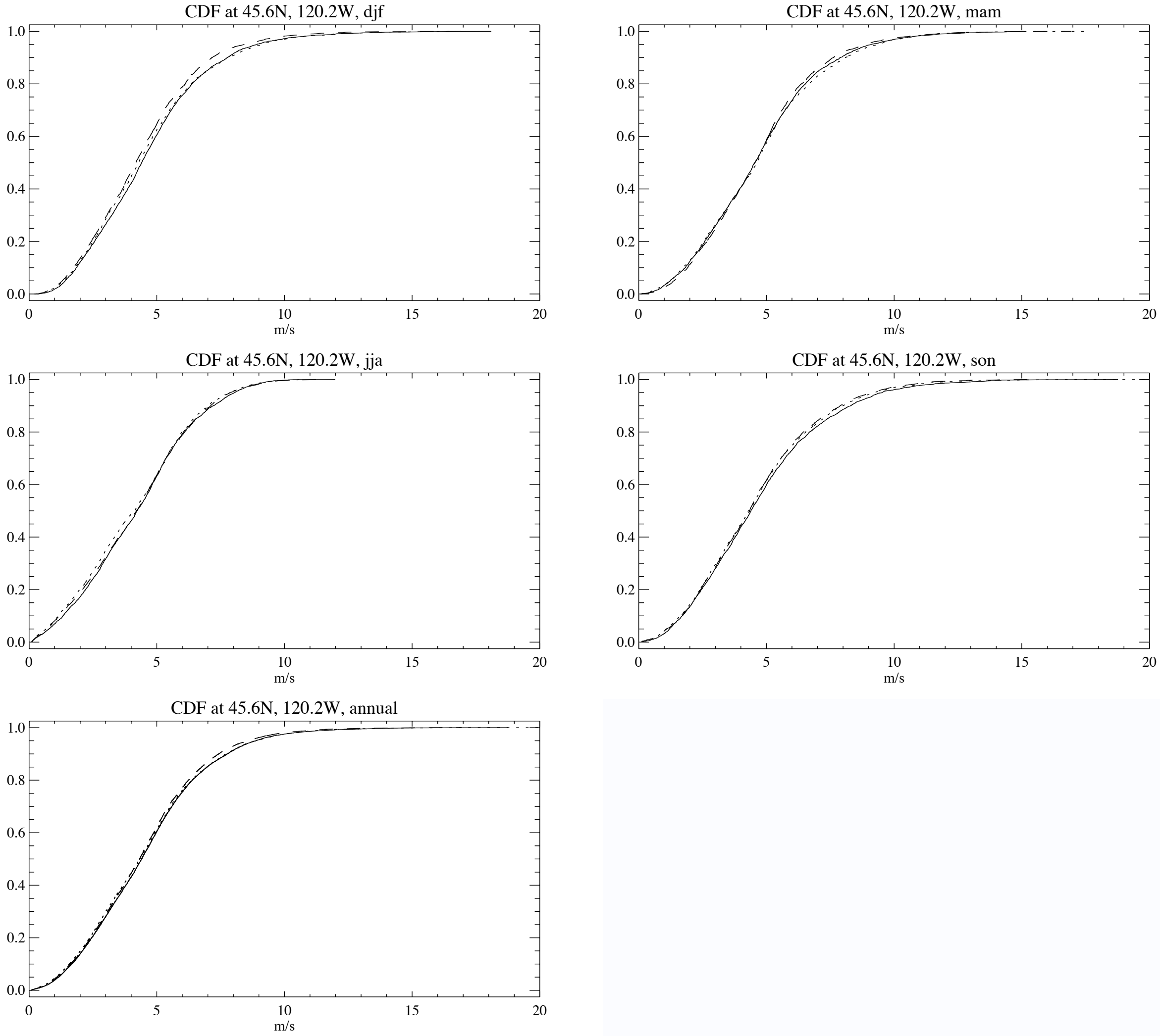

Figure 17. Cumulative density functions of wind speed at 45.6°N, 120.2°W, for three-month seasons (DJF= December-February, etc.) and annual (bottom left) for 1990s (solid), 2020s (dotted), and 2050s (dashed).

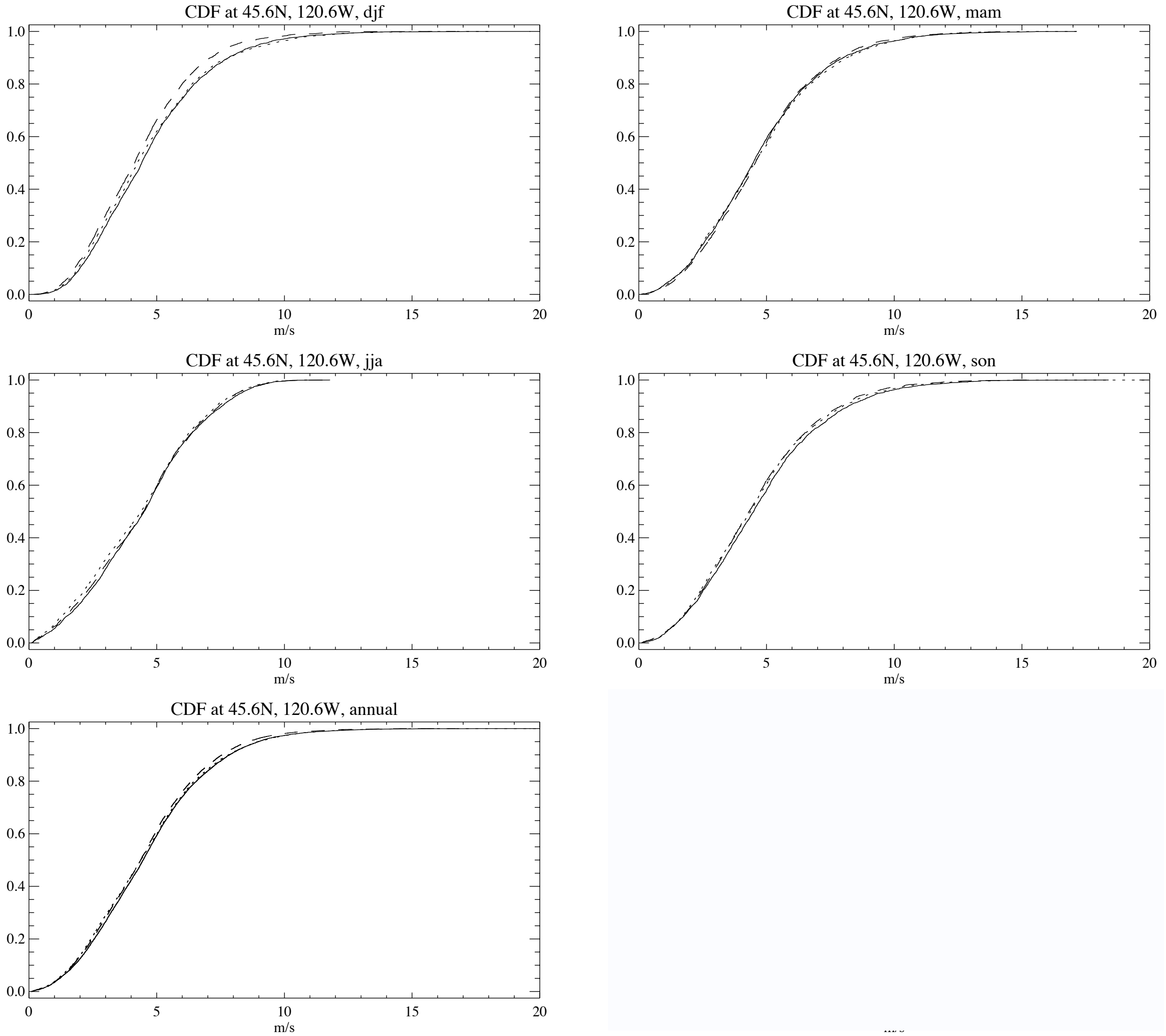

Figure 18. As in Figure 17 but for 45.6°N, 120.6°W.

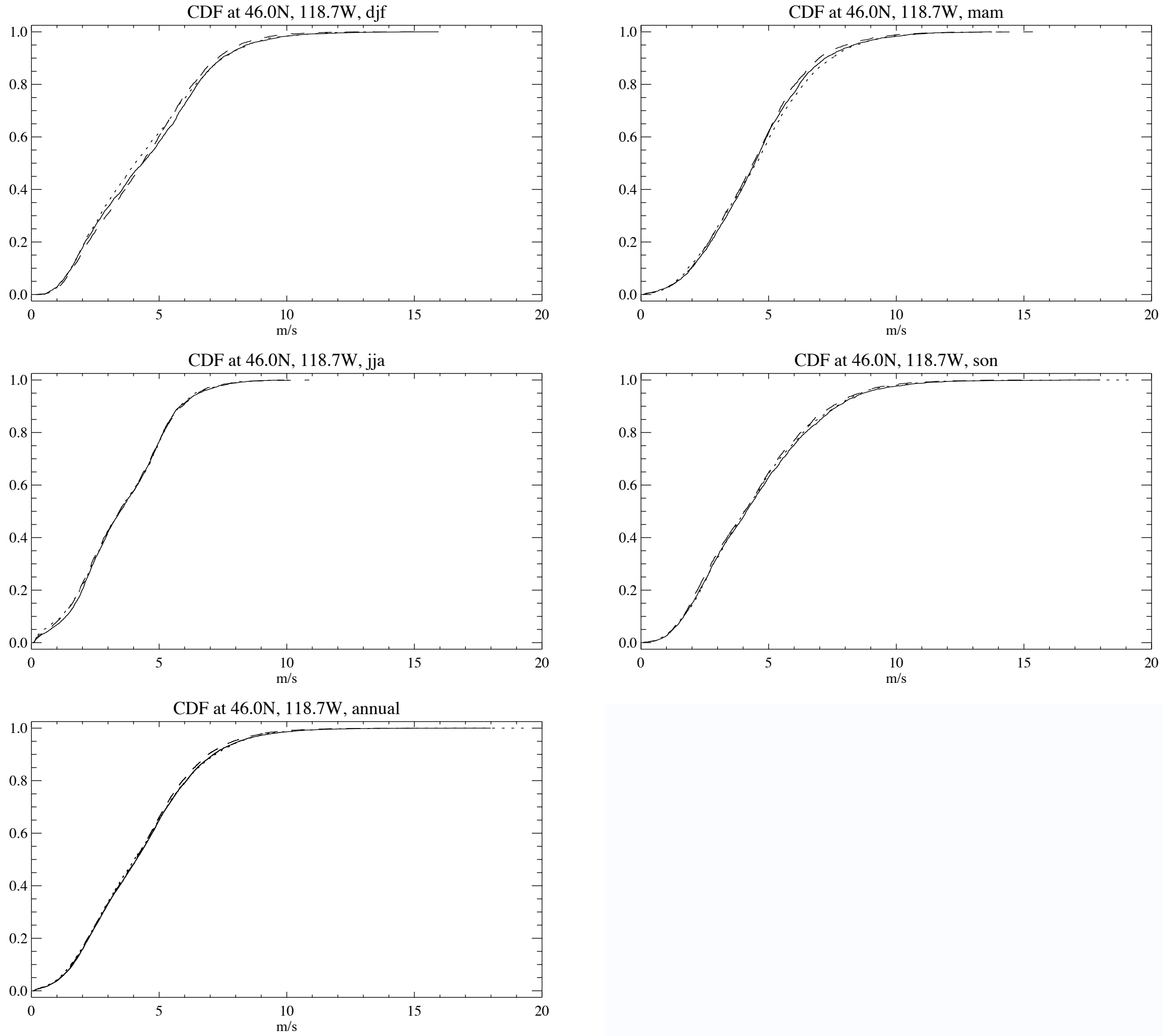

Figure 19. As in Figure 17 but for 46.0°N, 118.7°W.

7. Conclusions

We commend PGE for its curiosity about the effects of climate change. Funding for this project enabled us to examine the new round of climate scenarios, which resulted in a slight downward revision of projected temperature changes for technical reasons explained elsewhere (Mote et al. 2005b). The new scenarios also produced a surprising result that summer warming may exceed winter warming. Temperatures in the next 50 years are likely to far exceed those of the 20th century. Precipitation changes are unlikely to exceed those experienced in the 20th century, however.

Even with sizeable increases in precipitation, summer flow and summer hydro production are likely to decline in a warming world. The region needs to develop a coordinated approach to managing water resources under these changing circumstances.

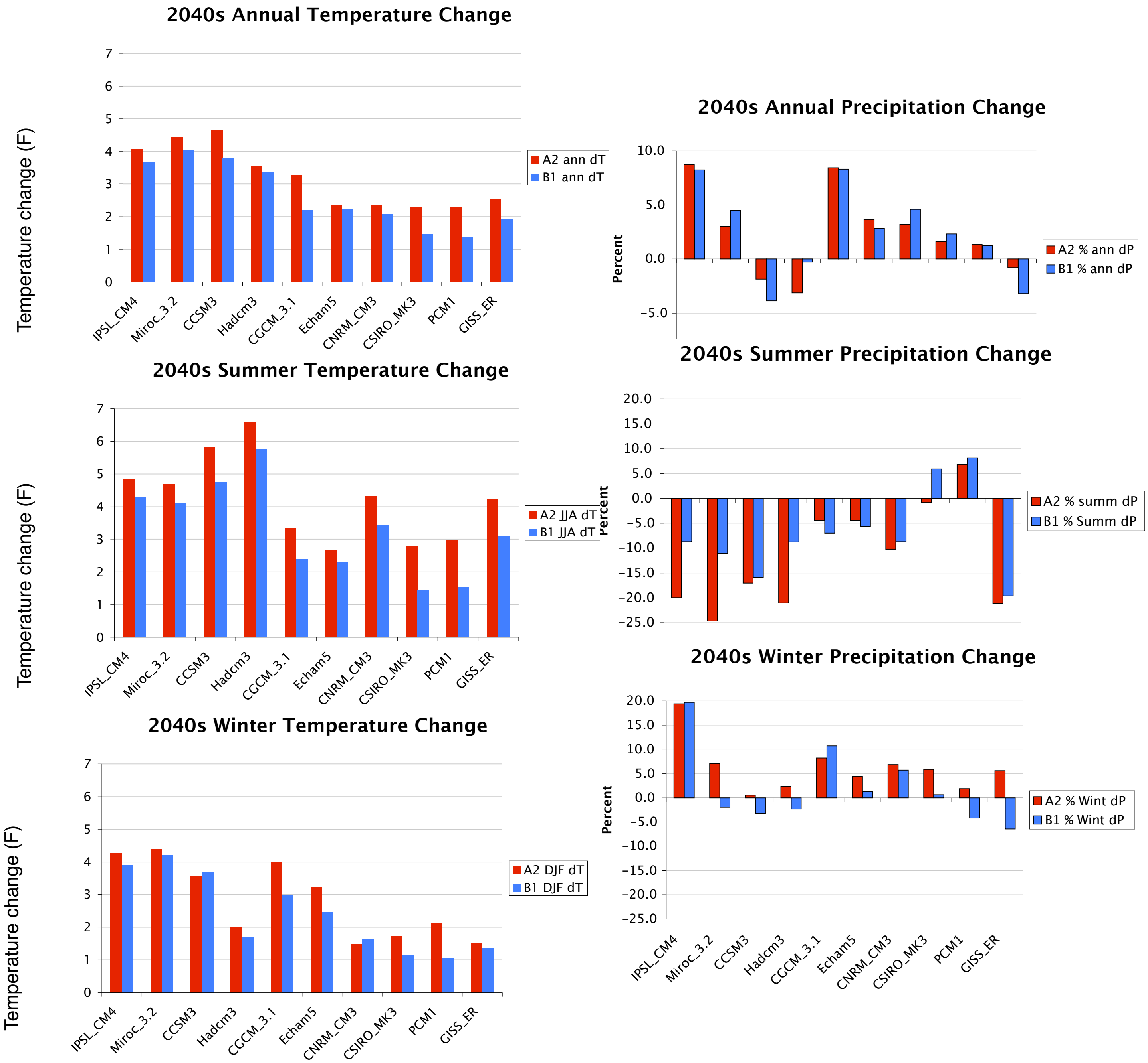

Figure 20. Details of the models' individual projections of temperature and precipitation change.

References and details about the models

Model	Institution	Version	Contact	References
ccsm3	NCAR (National Center for Atmospheric Research, Boulder, CO, USA)	CCSM3.0, version beta19 (2004): atmosphere: CAM3.0, T85L26 ocean: POP1.4.3 (modified), gx1v3 sea ice: CSIM5.0, T85 land: CLM3.0, gx1v3	ccsm@ucar.edu	Collins, W.D., et al., 2005: The Community Climate System Model, Version 3 Journal of Climate, Main website: http://www.ccsm.ucar.edu
cgcm_3.1	CCCma (Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada)	CGCM3.1 (2004): atmosphere: AGCM3 (GCM13d, T47L31) ocean: CCCMA (OGCM3.1,192x96L29)	Greg Flato (Greg.Flato@ec.gc.ca)	
cnrm_cm3	CNRM (Centre National de Recherches Meteorologiques, Meteo-France, Toulouse, France)	CNRM-CM3 (2004): atmosphere: Arpege-Climat v3 (T42L45, cy 22b+) ocean: OPA8.1 sea ice: Gelato 3.10 river routing: TRIP	david.salas@meteo.fr, sophie.tyteca@meteo.fr, jean-francois.royer@meteo.fr	D. Salas-Mélia, F. Chauvin, M. Déqué, H. Douville, J.F. Gueremy, P. Marquet, S. Planton, J.F. Royer and S. Tyteca (2004) : XXth century warming simulated by ARPEGE-Climat-OPA coupled system
csiro_mk3	CSIRO (CSIRO Atmospheric Research, Melbourne, Austrvalia)	CSIRO Mk3.0 (2000): atmosphere: spectral (T63L18) ocean: MOM2.2 (1.875x0.925L31)	Mark Collier (Mark.Collier@csiro.au), Martin Dix (Martin.Dix@csiro.au), Tony Hirst (Tony.Hirst@csiro.au)	Model described by Gordon et al. The CSIRO Mk3 Climate System Model, 2002, www.dar.csiro.au/publications/gordon_2002a.pdf
echam5	MPI (Max Planck Institute for Meteorology,Hamburg, Germany)	ECHAM5/MPI-OM(2004): atmosphere: ECHAM5 (T63L32) ocean: OM (1x1L41) sea ice: ECHAM5	Joerg Wegner (wegner@dkrz.de)	ECHAM5: E. Roeckner et. all, 2003,The atmospheric general circulation model ECHAM5Report No. 349OM: Marsland et. all, 2003,The Max-Planck-Institute global ocean/sea ice modelwith orthogonal curvelinear coordinatesOcean Modell., 5, 91-127.OM: Haak, H. et. all, 2003:Formation and propagation of great svalinity anomvalies,Geophys. Res. Lett., 30 , 1473,10.1029/2003GL17065.
giss_er	NASA/GISS (Goddard Institute for Space Studies)New York, NY	E3Af8aoM20A	Kenneth Lo (cdkkl@giss.nasa.gov)	www.giss.nasa.gov/research/modeling
hadcm	Met Office (Exeter, Devon, EX1 3PB, UK)	HadCM3 (1998): atmosphere: (2.5 x 3.75) ocean: (1.25 x 1.25) sea ice: land: MOSES1	jason.lowe@metoffice.gov.uk, simon.gosling@metoffice.gov.uk	Gordon, C., C. Cooper, C.A. Senior, H.T. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell and R.A. Wood, 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn., 16, 147-168. Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett and R.A. Wood, 1997. The Second Hadley Centre Coupled Ocean-Atmosphere GCM: Model Description, Spinup and Vvalidation. Clim. Dyn. 13, 103-134.
ipsl_cm4	IPSL (Institut Pierre Simon Laplace, Paris, France)	IPSL-CM4_v1	Sebastien Denvil, sebastien.denvil@ipsl.jussieu.fr	
miroc_3.2	CCSR/NIES/FRCGC (Center for Climate System Research, Tokyo, Japan / National Institute for Environmental Studies, Ibaraki, Japan / Frontier Research Center for Global Change, Kanagawa, Japan)	MIROC3.2 (2004): atmosphere: AGCM (AGCM5.7b, T42 L20) ocean & sea ice: COCO (COCO3.3, 256x192 L44) land: MATSIRO (T42)	Toru Nozawa (nozawa@nies.go.jp)	K-1 Coupled GCM Description (K-1 Technical Report No.1) in preparation
pcm1	NCAR (National Center for Atmospheric Research, Boulder, CO, USA)	Parallel Climate Model (PCM) version 1.1, (2000): atm : CCM3.6.6, (modified), T42L18 ocn : POP1.0 (modified),	pcm1@ucar.edu	Washington, W.M., et.al., 2000: Parallel climate model (PCM) control and transient simulations. Climate Dynamics, Volume 16 Issue 10/11 (2000) pp 755-774 Main website: http://www.cgd.ucar.edu/pcm

Additional information is available at http://www.atmos.washington.edu/~salathe/AR4_Climate_Models/

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