

Scenarios of future climate for the Pacific Northwest

a report by

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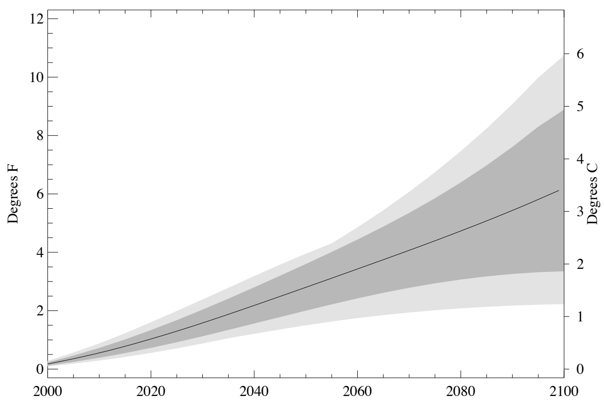
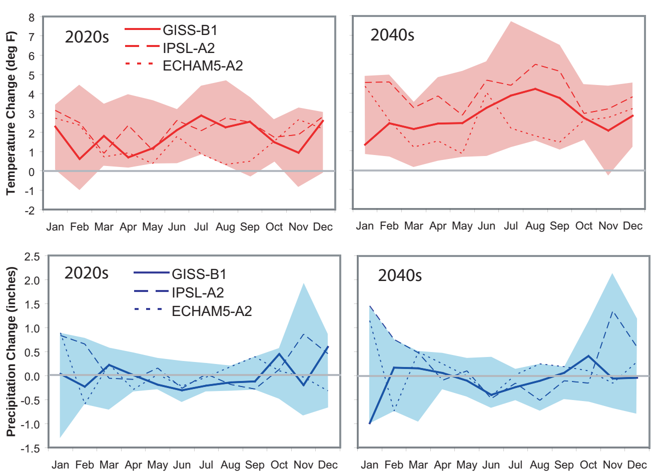
Summary.



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.

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. For comparison, observed warming in the 20th century was approximately 0.1°C per decade. Trends in temperature already stand out above natural variability.

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.

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%

2080s*	temperature	precipitation
low	1.6°C (2.9°F)	-2%
average	3.1°C (5.6°F)	6%
high	4.9°C (8.8°F)	18%

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

Details.

1. 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 1). The climate forcing of all scenarios is similar until mid-century.

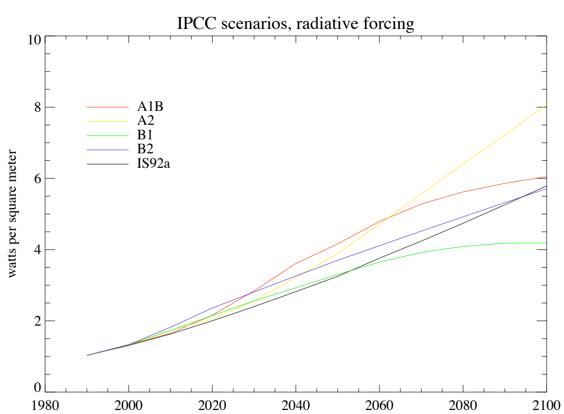


Figure 1. Globally averaged radiative forcing by greenhouse gases and sulfate aerosols, from IPCC (2001).

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.

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 CO_2 doubling in a simulation in which the CO_2 increased at 1%/year (roughly IS92a, the black curve in Figure 1). 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, page 4). This method 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.

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.

2. 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 2-4, and there are large differences between the two "observed" averages (Figures 3-4). A quantitative evaluation of the relative merits of the various estimates of "observed" climate is beyond the scope of this paper but worth pursuing.

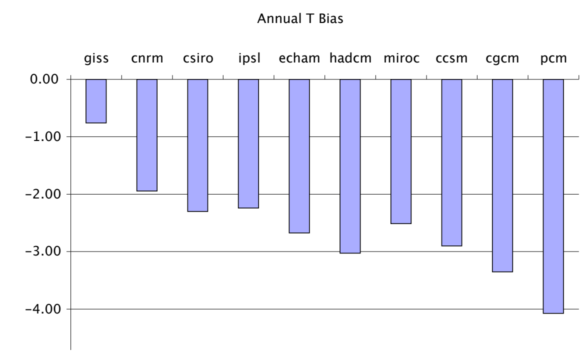


Figure 2. Difference (°C) between each model's mean annual temperature and observed temperature for the Pacific Northwest, for 1970-99 using climate division data.

The models are uniformly too cold (Figure 2) and this largely determines the root-mean-square (rms) error of their seasonal cycle, which is how they are ranked in Figure 2. The same ranking is used to present the rms error of the seasonal cycle in precipitation (Figure 3). Two of the models are much worse than the others, owing to their very wet winter climate (Figure 4).

As shown in Figure 4, the models represent the gross features of the Northwest's mean seasonal cycle, including the dry winters and wet 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.

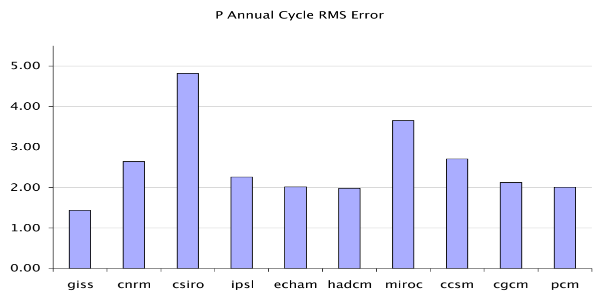


Figure 3. Each model's rms error in mean monthly precipitation, averaged over each month of the year. Order of models is the same as in Figure 2.

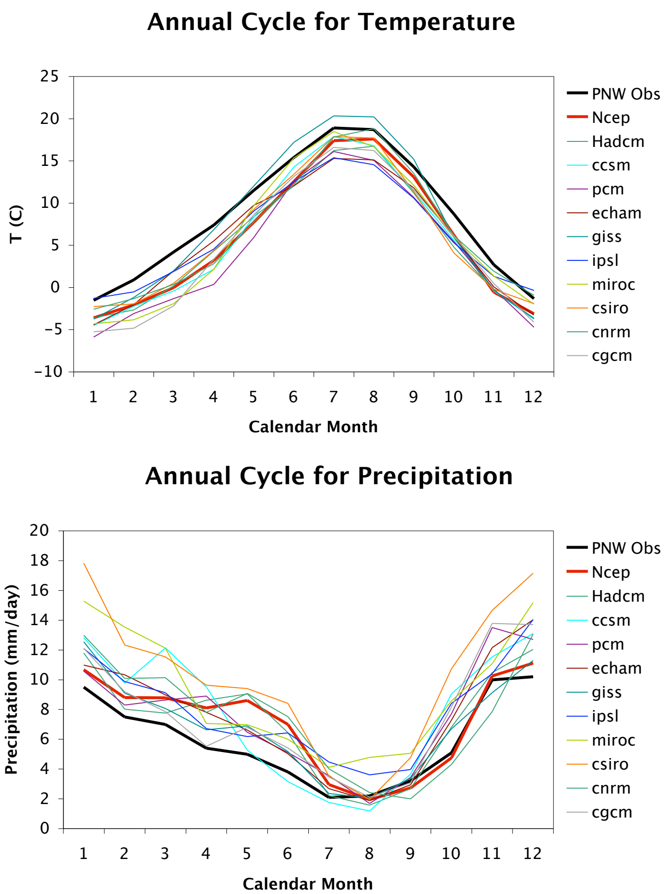


Figure 4. Mean seasonal cycle for each climate model from its 20th century simulation, compared with observations estimated from climate division data (black) and the NCEP/NCAR reanalysis (red).

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 0.6°C warming observed in the 20th century. 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.

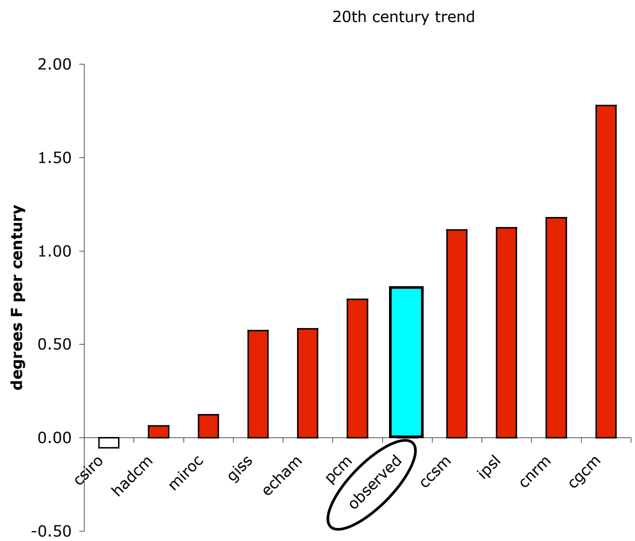


Figure 5. Linear trend in temperature for the Pacific Northwest during the 20th century for each of the 10 models from simulations forced by observed changes in greenhouse gases. The observed trend is shown in blue.

3. 21st century trends in the annual mean

The annually averaged, regionally averaged temperature for all 20 simulations is shown in Figure 6, 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 scenarios, owing to the markedly different radiative forcing. Note also the different warming rates in the 20th century.

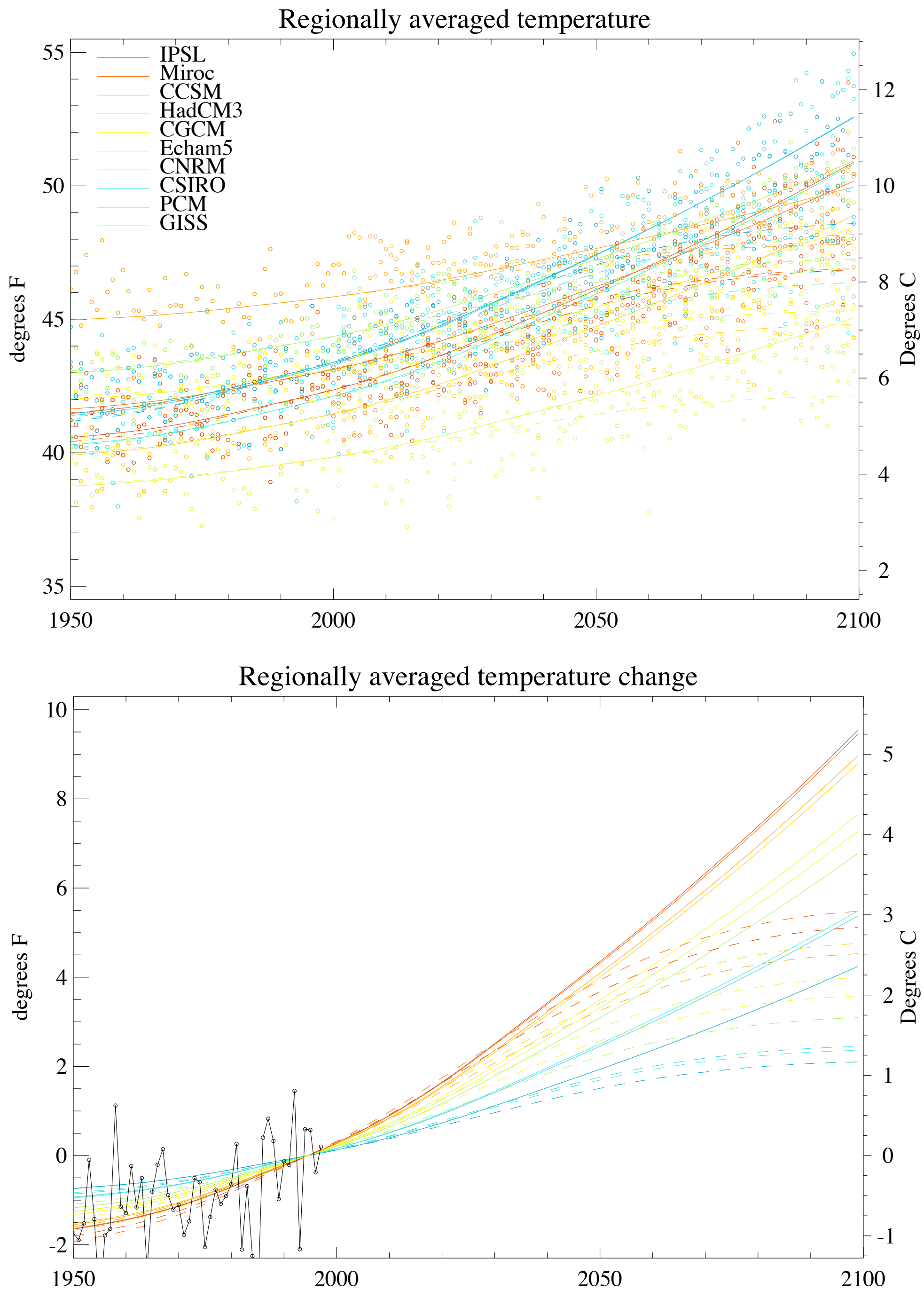


Figure 6. In the top panel, each symbol represents one year's temperature in one simulation. Smooth curves are drawn for each simulation; A2 scenarios are solid, B1 dashed. Models are color-coded according to their warming rate in the A2 scenario. In the bottom panel, the smooth curves from the top panel 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 7). 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.

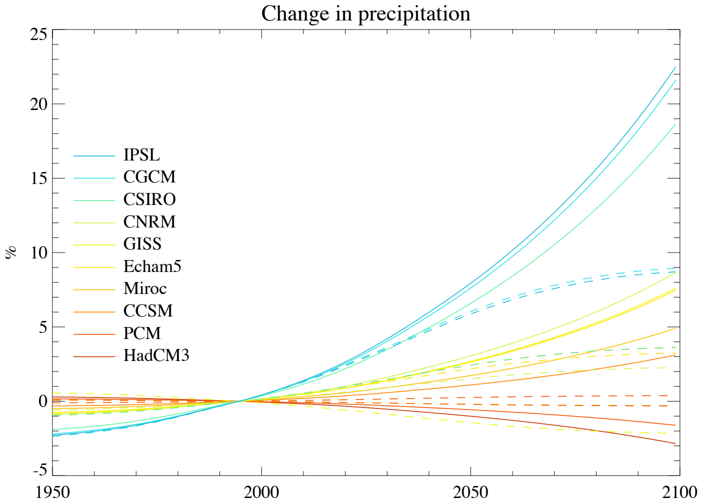


Figure 7. Smoothed precipitation traces for the 20 model simulations are shown as in Figure 6b. For preparing the summary table shown on page 1, 30-year averages were used, and the answers are substantially similar. Models are ranked from driest (red) to wettest (blue).

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 8). 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.

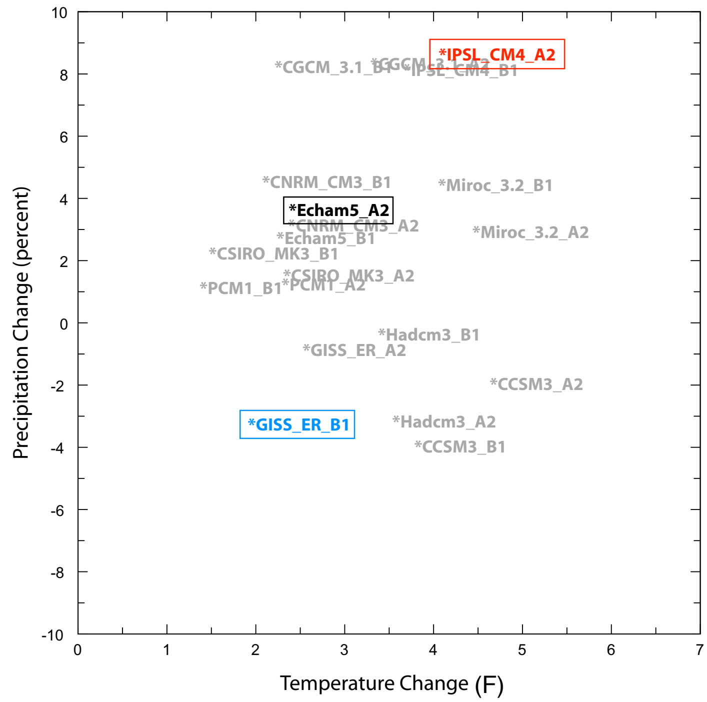


Figure 8. Scatterplot of change in annually averaged temperature and precipitation for each of the 20 scenarios, for the "2040s" (i.e., 2030-2059 minus 1970-99). Three suggested "marker" scenarios are highlighted.

For more detailed modeling studies that require output from an actual climate model, we suggest the three scenarios highlighted in Figure 8 to represent (1) a relatively high rate of warming and large increase of precipitation (the IPSL A2 scenario); (2) a middle-of-the-road scenario (ECHAM5 A2); and (3) a cooler, drier scenario (GISS B1). These are summarized in Tables 2 and 3. We stress that the ranking of these scenarios is not the same for other decades, and that for situations where seasonality may play a role other models may better represent the extremes in the range of possibilities. For example, as we will show in the next section, HadCM3 has extremely high increases in summer temperature.

temperature (°F)	2020s	2040s	2080s
GISS-B1	1.79	1.91	2.92
ECHAM-A2	1.42	2.37	6.68
IPSL-A2	2.20	4.06	8.71

Table 2. Summary of changes in annual temperature for the three scenarios marked in Figure 8. "2020s" refers to the 2010-2040 average minus the 1970-2000 average, the latter taken from the model's 20th century simulation, and likewise for "2040s" and "2080s".

precipitation (%)	2020s	2040s	2080s
GISS-B1	-0.2	-3.3	-0.3
ECHAM-A2	1.0	4.0	4.7
IPSL-A2	6.1	8.7	17.7

Table 3. As in Table 2 but for changes in precipitation.

Other aspects of climate change may be very important as well but are not explored here: wind speed, direction, and extremes; frequency of extreme cold, hot, wet, or dry events; cloudiness.

4. Seasonality of changes in climate.

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 and forest fires.

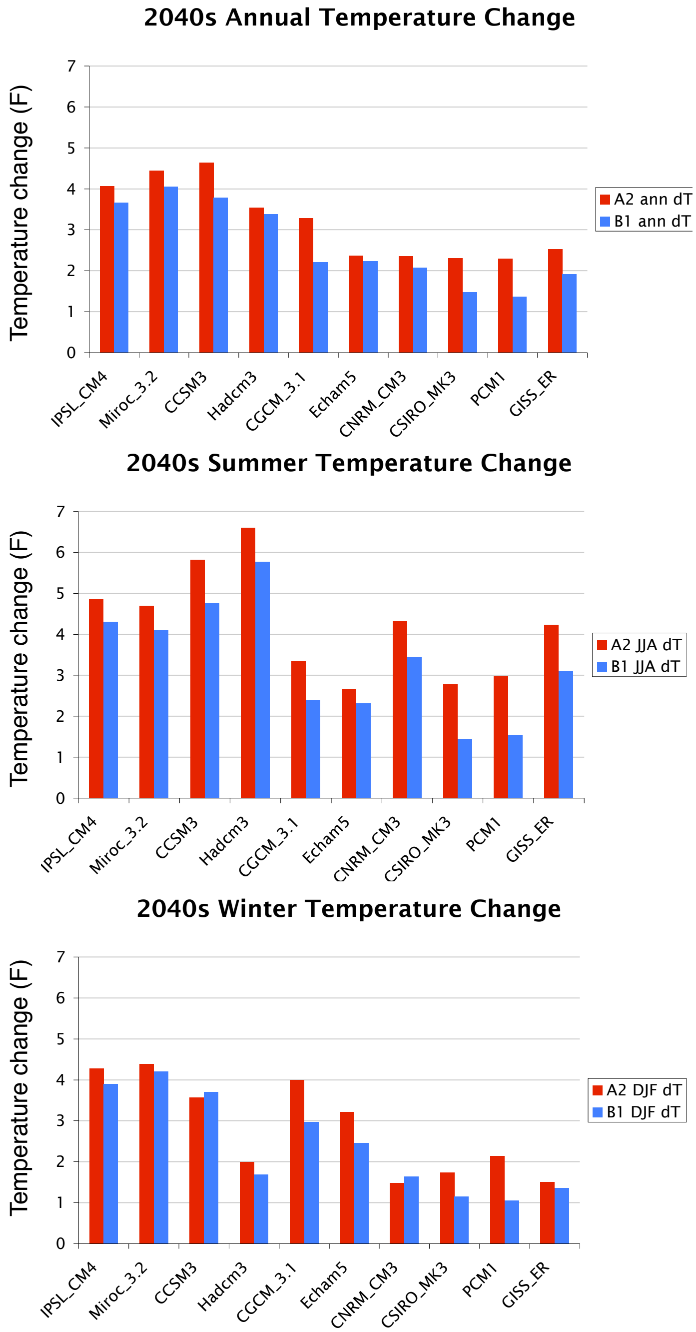


Figure 9. Changes in temperature, "2040s" (2030-2059 average minus 1970-99 average), for 20 scenarios. Top: annual mean; middle: June-August; bottom: December-February.

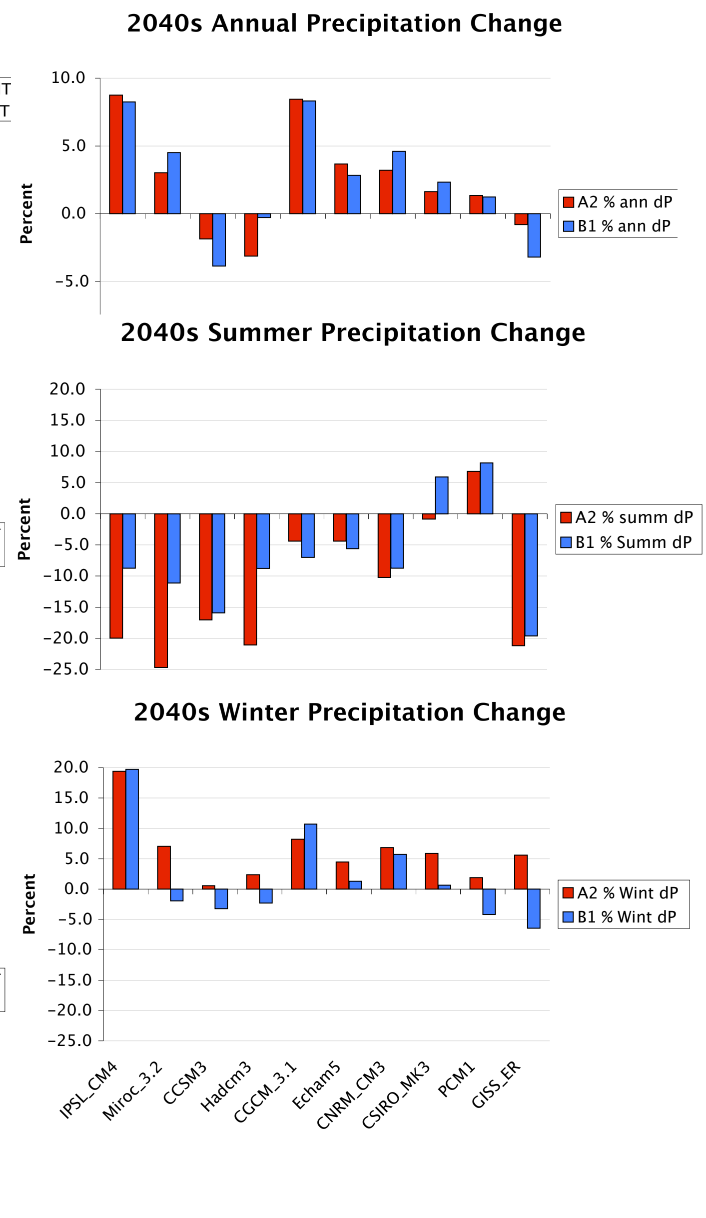


Figure 10. As in Figure 9 but for precipitation. Most models project decreases in summer precipitation and increases in winter precipitation, with little change in the annual mean.

Precipitation changes are largest in winter (December-February), and tend to be positive. In summer, precipitation declines slightly in most scenarios. The seasonality of changes is further illustrated in Figure 11.

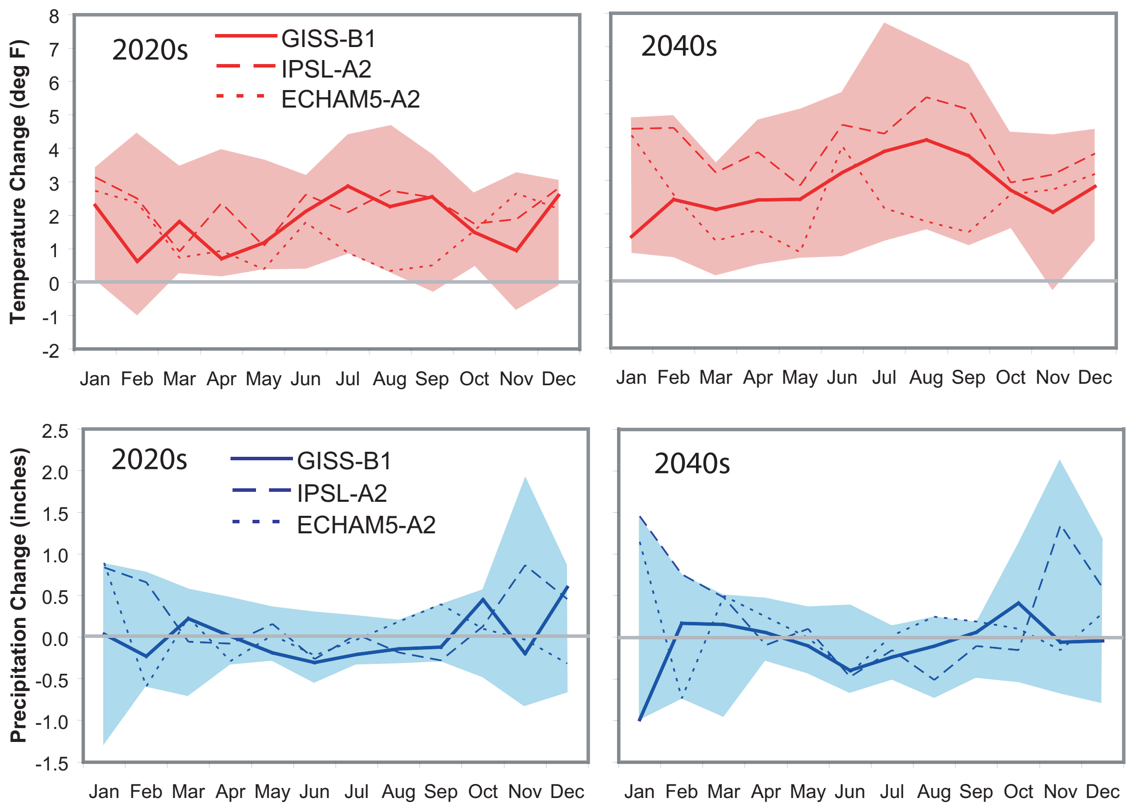


Figure 11. Changes in temperature (top) and precipitation (bottom) month by month, for all scenarios (shaded envelopes) and for the three marker scenarios.

5. Discussion of differences from previous scenarios.

Owing primarily to differences in the baselines used, these new scenarios show smaller changes in temperature than the scenarios previously promulgated by the UW Climate Impacts Group (Table 4). Projected warming is substantially less for the 2020s, where previously the central estimate was 1.7°C.

Previously, the baseline was calculated from long "control" simulations in which carbon dioxide was held fixed. Each modeling group chose a different control value of CO_2, some appropriate for ~1900 and some for ~1995, which meant that the baselines included different degrees of 20th-century warming. Mote et al. (2003) attempted to correct for these differences, bringing the minimum and mean closer to the new scenarios (0.5°C and 1.5°C, respectively) but the warming rate from 1990s to 2020s was still rather large. The new approach to calculating the baseline, a 30-year mean from the model's simulation of 20th century, provides a common framework that overcomes this earlier deficiency.

temperature	2020s		2040s	
(°C)	old	new	old	new
lowest	1.4	0.4	1.7	0.8
average	1.7	1.1	2.3	1.6
highest	2.1	1.8	2.9	2.6

Table 4. Comparison of low, average, and high scenarios used by Snover *et al.* [2003] and in the new work.

Another factor influencing the results was that the models of the earlier generation used a simple 1%/year assumption of CO_2 growth, which is substantially above the observed rate of 0.4%. Hence, the change radiative forcing between a given decade of the control simulation and the 2020s was higher.

Finally, the new scenarios are based on 20 models rather than just eight, increasing the likelihood that the range of projected changes will increase.

Precipitation changes were previously reported as ten-year averages, which meant that substantial model variability was included. Using 30-year means or the log-CO_2 smoothing sifts through the variability to focus on longer-term change. Consequently, the projected changes in precipitation are smaller for the 2020s than previously reported (Table 5), especially at the high end owing to the fact that the 2020s were a wet decade in the HadCM2 simulation.

precipitation	2020s		2040s	
%	old	new	old	new
lowest	2	-4	-3	-4
average	6	2	4	2
highest	14	6	9	9

Table 5. As in Table 4 but for precipitation.

6. References

Details about the climate 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/

Greenhouse gas scenarios and information about earlier climate models from

IPCC 2001: *Climate Change 2001: The Scientific Basis*. J.T. Houghton et al., eds. Cambridge University Press, Cambridge, UK. 881 pp.

Previous model scenarios for the Northwest have been reported in, for example,

Hamlet, A.F., and D.P. Lettenmaier, 1999: Effects of climate change on hydrology and water resources in the Columbia River Basin. *Journal of the American Water Resources Association* 35(6):1597-162,

Snover, A. K., A. F. Hamlet, and D. P. Lettenmaier. 2003. Climate change scenarios for water planning studies: Pilot applications in the Pacific Northwest. *Bulletin of the American Meteorological Society* 84(11):1513-1518.

and

Mote, P. W., E. A. Parson, A. F. Hamlet, K. N. Ideker, W. S. Keeton, D. P. Lettenmaier, N. J. Mantua, E. L. Miles, D. W. Peterson, D. L. Peterson, R. Slaughter, and A. K. Snover. 2003. Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest. *Climatic Change* 61:45-88.