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PREPARING FOR CLIMATIC CHANGE: THE WATER, SALMON, AND FORESTS OF THE PACIFIC NORTHWEST

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Abstract. The impacts of year-to-year and decade-to-decade climatic variations on some of the Pacific Northwest's key natural resources can be quantified to estimate sensitivity to regional climatic changes expected as part of anthropogenic global climatic change. Warmer, drier years, often associated with El Niño events and/or the warm phase of the Pacific Decadal Oscillation, tend to be associated with below-average snowpack, streamflow, and flood risk, below-average salmon survival, below-average forest growth, and above-average risk of forest fire. During the 20th century, the region experienced a warming of 0.8 °C. Using output from eight climate models, we project a further warming of 0.5–2.5 °C (central estimate 1.5 °C) by the 2020s, 1.5–3.2 °C (2.3 °C) by the 2040s, and an increase in precipitation except in summer. The foremost impact of a warming climate will be the reduction of regional snowpack, which presently supplies water for ecosystems and human uses during the dry summers. Our understanding of past climate also illustrates the responses of human management systems to climatic stresses, and suggests that a warming of the rate projected would pose significant challenges to the management of natural resources. Resource managers and planners currently have few plans for adapting to or mitigating the ecological and economic effects of climatic change.

1. Introduction

Certain natural resources feel the influence of climatic variability and change, and knowledge of those influences could improve long-term management of natural resources. This paper examines the influence of past climatic variability and likely future climatic change on three key climate-sensitive resources in the Pacific Northwest (PNW), namely, water, salmon, and forests. Undergirding the work is a retrospective analysis of connections between climatic variations and each resource. This retrospective approach also allows us to examine how the region's

Climatic Change **61:** 45–88, 2003.

natural resource management has reacted to past climatic variations, especially the stresses of extreme events like droughts. With this foundation, speculation about the impacts of future climatic change and the reactions of human institutions gains more credibility. Parts of this work, undertaken by the interdisciplinary Climate Impacts Group at the University of Washington, have previously been reported elsewhere (Mote et al., 1999b; Parson et al., 2001). This paper extends these earlier efforts in several ways, including by introducing common cross-disciplinary analysis and by considering the adaptive capacity of natural resource management.

Our assessment of the regional impacts of climatic variations and change is placed in the context of other regional stresses, notably population growth, declines in many salmon runs, and federally mandated reductions in harvest of timber and salmon. Population has nearly doubled since 1970, a growth rate nearly twice the national average. Human activities strain the natural environment in many ways, including direct human interventions in the landscape through such activities as dam building, timber harvest (which has also widely replaced diverse natural forests by single-species plantations), and land-use conversion from the original forests, wetlands, grasslands and sagebrush to expansion of metropolitan areas, intensively managed forests, agriculture and grazing. The consequences include loss of old-growth forests, wetlands, and native grass and steppe communities; urban air pollution; extreme reduction of many salmon runs; and increasing numbers of threatened and endangered species.

The PNW (topography shown in Figure 1) has a great diversity of climates and resources. Over fairly short distances ecosystems range from desert to lush rain forest to alpine meadows, owing largely to the mountains and their influence on climate. The close proximity of mountain and marine environments, especially where they are richly entwined around the Puget Sound area, makes for strong reciprocal influences of the two types of environments on each other. The region is divided climatically, ecologically, economically, and culturally by the Cascade Mountains. Manufacturing, trade and services dominate the economy west of the Cascades, while agriculture is much more important east of the Cascades thanks to irrigation, fertile soils, and abundant sunshine.

The next section describes the region's climate, 20th century patterns of climatic variation, and the changes in mean climate projected by climate models for the first half of the 21st century. In Sections 3, 4, and 5, we consider the relationship between climate and the region's water, salmon, and forests, first describing the influence of mean climate, then the influence of climatic variations like El Niño, and finally our best estimates of the influence of climatic change. In Section 6 we consider institutional issues and the region's adaptive capacity.

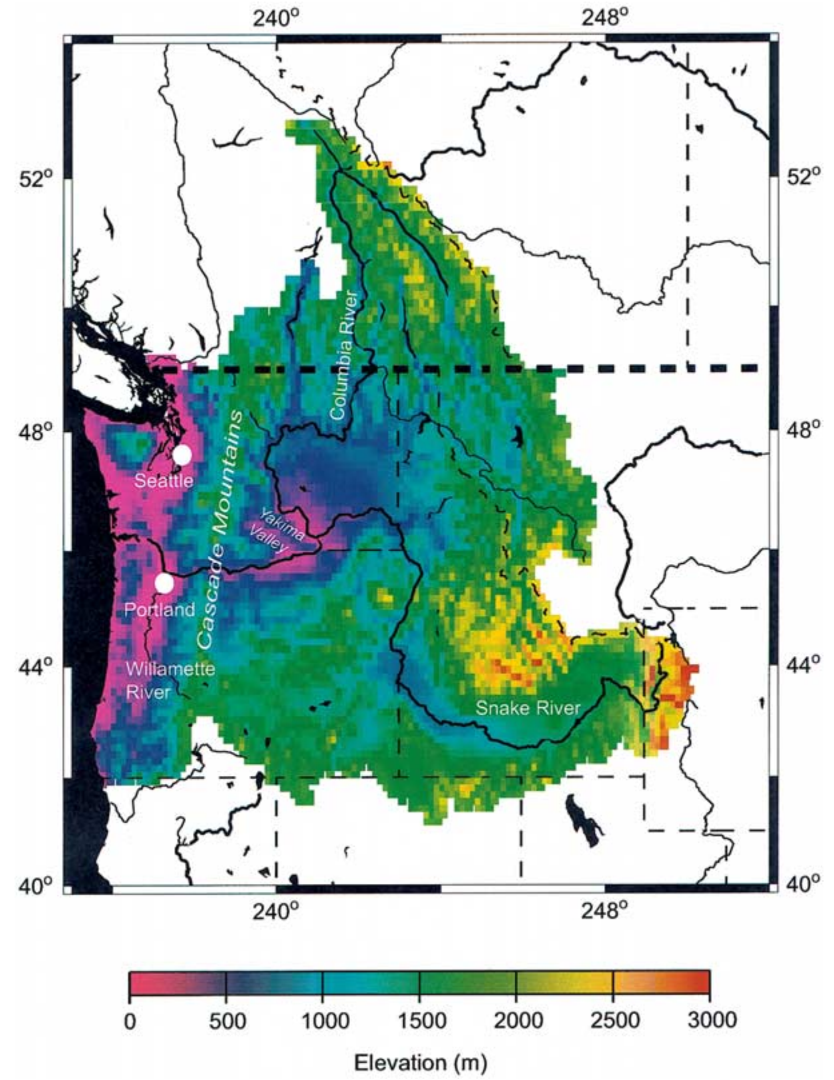

Figure 1. Map of Pacific Northwest with topography indicated by color, and main features labeled.

2. Climatic Variability and Change

West of the Cascades the climate of the Northwest is ‘maritime’, with abundant winter precipitation, dry summers, and mild temperatures year-round. Most places west of the Cascades are usually above freezing in winter, so snow seldom stays on the ground more than a few days except at higher elevations. Except for a small area in the rain shadow of the Olympics, almost every area west of the Cascades receives more than 75 cm of precipitation annually, while some western mountain slopes of the Olympics and Cascades receive more than 500 cm. East of the Cascade crest,

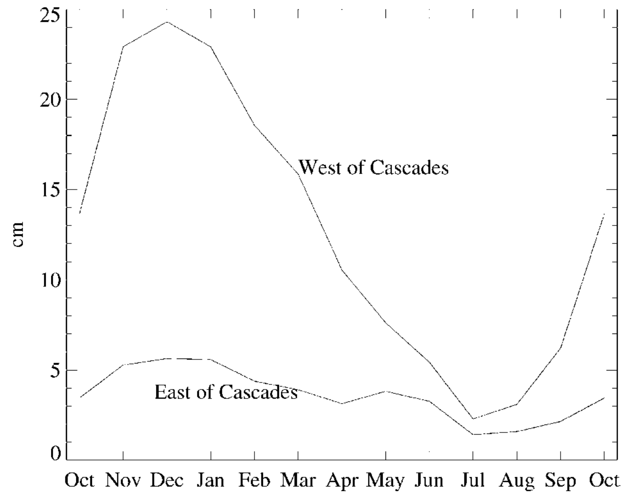

Figure 2. Average monthly precipitation (using Climate Division data) in the Pacific Northwest, west and east of the Cascade crest.

the climate shifts sharply from abundant rainfall to abundant sunshine, with annual precipitation generally less than 50 cm and as little as 18 cm in some places. Even mountainous areas east of the Cascade crest receive much less precipitation than the western Cascades or Olympics. The seasonality in precipitation is strongest west of the Cascades, where the wettest month is almost 10 times as wet as the driest month (Figure 2). Summer precipitation in the west is only slightly higher than in the east. Though average temperatures are similar east and west, the east has larger daily and annual ranges, with hotter summers and colder winters.

2.1. OBSERVED CLIMATIC PATTERNS

While climate varies a great deal from place to place across the Northwest, variations in climate from year to year are strongly correlated across the region.⋆ Put simply, warm years tend to be warm, and cool years cool, everywhere in the region. This regional coherence simplifies our analysis by permitting us to focus on temporal fluctuations in the regional average anomalies.

Year-to-year global climatic variations are dominated by El Niño/Southern Oscillation (ENSO), an irregular oscillation of the tropical atmosphere and ocean with a period of 2 to 7 years (e.g., McPhaden et al., 1998). Much of western North America is also influenced by the more recently named Pacific Decadal Oscillation (PDO) pattern (Mantua et al., 1997), defined as the leading mode of variations in

⋆ Using climate division data (see appendix) for the three Northwest states, we calculated correlations of annual temperature time series in different locations (climate divisions). Among all the pairs of climate divisions, the average correlation was 0.78, with a range from 0.41 to 0.98. Correlations for annual precipitation anomalies are somewhat lower, averaging 0.55 with a range from –0.01 to 0.96.

monthly anomalies of Pacific sea surface temperature (SST) north of 20° latitude. The spatial patterns of SST are similar for ENSO and PDO, but PDO's footprint in SST is stronger in the central and northern Pacific than near the equator, and its irregular period is several decades; in the 20th century, PDO tended to stay in one phase or the other for 20 to 30 years at a time. PDO is also much less well understood than ENSO, in part because its period is so long relative to the history of reliable records that only two complete oscillations have been observed. The PDO was in its cool, or negative, phase from 1900 until 1925, then in the warm phase until 1945, cool phase again until 1977, and warm phase until the 1990s. Another cool phase of PDO may have begun in 1998, but it is too early to tell with confidence and its likely duration is unknown (Hare and Mantua, 2000). Tree ring records (Gedalof and Smith, 2001) suggest that the size and frequency of 20th century shifts of the PDO are similar to those between about 1660 and 1840, but the period from 1840 and 1923 had less interdecadal and more interannual variability.

Warm phases of ENSO and PDO tend to coincide with winter and spring weather that is warmer and drier than average in the PNW, and cool phases tend to coincide with cooler wetter weather (Figure 3, top two rows). The warm-cool difference is about 1 °C for temperature and 20% for precipitation. These climatic anomalies influence important natural resources, as shown in the rest of Figure 3 and as will be discussed in Sections 3–5.

These two climate patterns are useful for our purposes in at least two ways. First, together they provide some of the best predictability in seasonal forecasts of any middle latitude location. Second, the multi-decadal timescale of the PDO may provide a useful surrogate for anthropogenic climate change. For some natural resources, as will be shown below, the persistence of warmer-drier or cooler-wetter conditions over 20–30 years produces a very different response than does a single anomalous year.

In addition to the year-to-year and decade-to-decade fluctuations in temperature and precipitation noted above, the region has experienced a trend toward warmer, wetter conditions. At all but a few of the 113 U.S. Historical Climate Network (HCN; Karl et al., 1990) stations in the Northwest, linear temperature trends have been between +0.5 and +2.0 °C per century (evaluated at each station from the beginning of the record, which for 95% of the stations is before 1916, until 1997; Mote et al., 1999b) and the regionally averaged trend is +0.82 °C per century, statistically significant at the 99% confidence level. At the 76 HCN stations with good precipitation records, precipitation trends are also mostly positive and in many cases quite large, with a regional average of about +14% (not statistically significant) per century (Mote et al., 1999b). Only 7 of the 76 stations have trends significant at the 95% confidence level, none at the 99% level. While the temperature increase has been fairly uniform throughout the year, much of the precipitation increase is concentrated in a few months (April, July, August, and December).

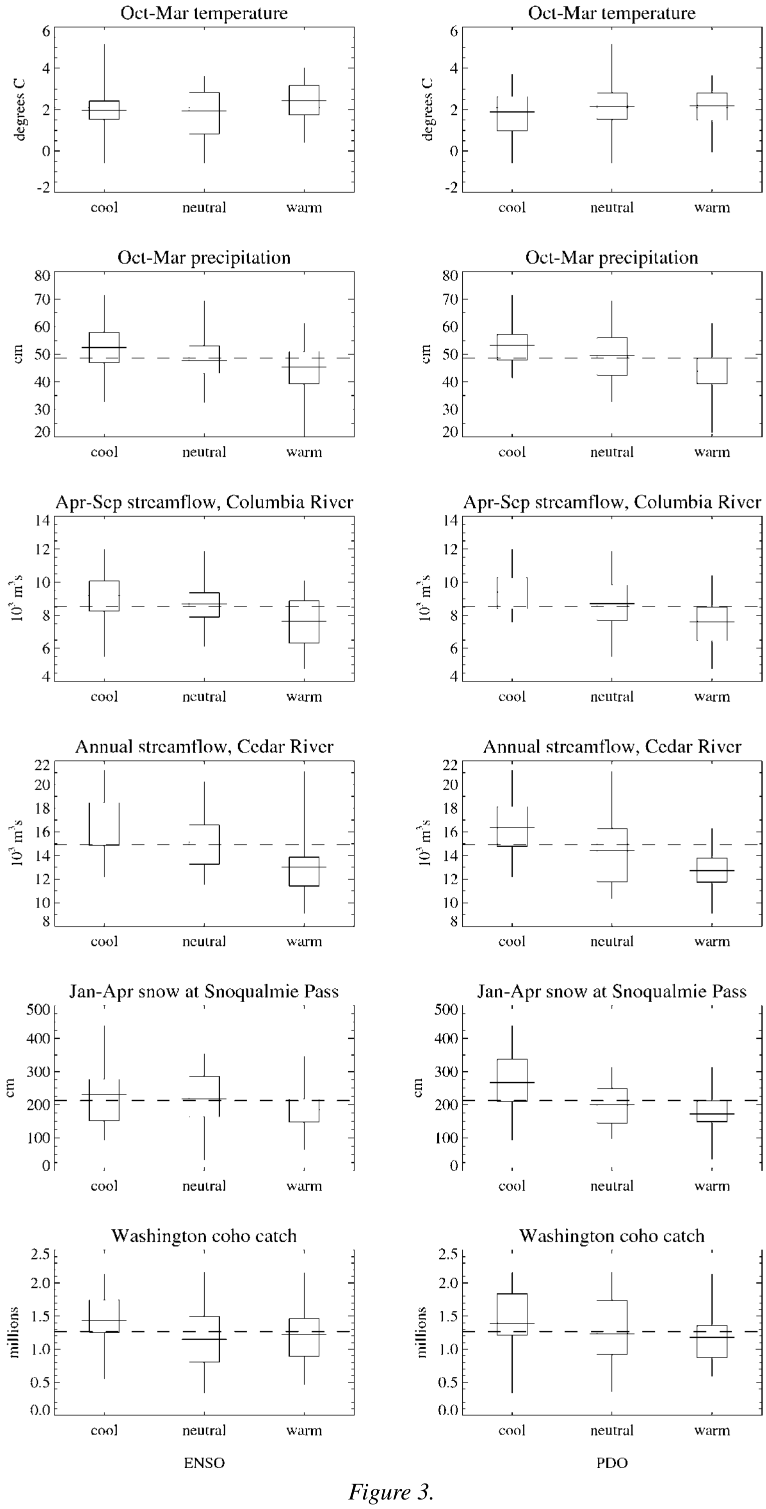
Oct-Mar temperature
degrees C
Oct-Mar precipitation
cm
Apr-Sep streamflow, Columbia River
10^3 m^3/s
Annual streamflow, Cedar River
10^3 m^3/s
Jan-Apr snow at Snoqualmie Pass
cm
Washington coho catch
millions
cool
neutral
warm
ENSO
PDO

Figure 3.

2.2. SCENARIOS OF FUTURE CLIMATE

We used output from eight different coupled global ocean-atmosphere climate models* available through the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre. All of these models included ocean, sea ice, and land surface models, though of varying complexity and spatial resolution. The simulations used time-varying, or 'transient', climatic forcing by carbon dioxide (CO_2) and anthropogenic sulfate aerosol. Sulfate aerosol have a cooling effect on parts of the planet's surface and are represented in the models by increased atmospheric albedo (reflectivity). Most of the simulations included the years 1900 to 2100. The evolution of equivalent CO_2 concentrations followed observed values until about 1994, and then increased at roughly 1% per year (some runs used the IPCC scenario IS92a, which is close to 1%/year, and some used exactly 1%/year).

To translate the output of these climate models into quantities useful for estimating some impacts of climate change, we use the fact that the region's climate shows a high degree of spatial coherence (Section 2.1) and consider only regionally averaged change. Studies of regional climatic change sometimes use models with significantly higher spatial resolution, which (at significant computational expense) can more realistically simulate the intricate texture of the region's climate. Leung and Ghan (1999a,b) have simulated the climate of the PNW using a regional, limited-domain model (the PNNL RCM), and the spatial *distributions* of temperature and precipitation are indeed simulated better, but the errors that they report in regional, seasonal averages are similar to those for the global climate models. Furthermore, the advantage of a regional model diminishes when considering *changes* in climate; one study comparing output from global and finer-scale regional climate models for western Canada suggested that changes in temperature are roughly the same with both types of models, while changes in precipitation are very different (Laprise et al., 1998) and can be difficult to interpret (i.e., are not obviously linked to topography).

* CCSR, Emori et al., 1999; CGCM1, Boer et al., 2000; CSIRO, Gordon and O'Farrell, 1997; ECHAM4/OPYC, Roeckner et al., 1996; GFDL, Manabe and Stouffer, 1996; HadCM2, Johns et al., 1997; HadCM3, Gordon et al., 2000; and NCAR PCM3, Washington et al., 2000.

Figure 3 (facing page). Box-and-whisker plots showing the influence of ENSO (left column) and PDO (right column) on the region's climate, water resources, and salmon. For each column, years are categorized as cool, neutral, or warm. For each climate category, the distribution of the variable is indicated as follows: range, whiskers; mean, horizontal line; top and bottom of box, 75th and 25th percentiles. Area-averaged Climate Division data (1899–2000) are used for temperature and precipitation, naturalized or 'virgin' flow data at the Dalles (1900–1998) are used for Columbia River streamflow, observed inflow at Chester Morse reservoir (1946–1993) are used for data from the Cedar River in Washington, semimonthly snow depth data from the Northwest Weather and Avalanche Center are used for snow depth at Snoqualmie Pass, Washington (1929–1997). The salmon catch data (Hare and Mantua, 2000) span 1924–1993 and are lagged so that the climate data correspond to year of ocean entry. Note how cool phases favor cool wet winters with more streamflow and more abundant salmon, and note the large shifts in distribution for streamflow.

We examine output from these eight global climate models in two ways. First, we examine the complete history of three of the models in order to compare their performance during the 20th century with observations. Second, we look at changes from control to the 2020s and 2040s from all eight models in order to provide a range of future climatic scenarios.

Transient simulations from 1900 to 2050 of CGCM1, ECHAM4, and HadCM2 are presented in Figure 4a. Despite their shortcomings, the models are fairly successful at reproducing many features of observed climate. The errors in simulated 20th century annual average temperature (the models are too cool by 0.5–1.7 °C) are smaller than in most land areas (IPCC, 2001a, p. 480). For precipitation, the models simulate a climate that is too wet by 17% (ECHAM4) to 53% (HadCM2), but the seasonality is roughly correct; the ratios of October–March precipitation to April–September precipitation range from 2.21 to 2.44, and the observed ratio is 2.43. The temperature trends are close to those observed (0.82 °C/century) for CGCM1 (0.70 °C/century) and ECHAM4 (0.92 °C/century), but not for HadCM2 (–0.3 °C/century). In the transient simulations, as in the observations, there is only a little warming from the 1900s to the 1970s, but then the pace of warming accelerates, and the warming rate per decade from the 1970s to the 2040s resembles the warming rate observed from the 1970s to 1990s. The three models have very different decadal variability, from almost none (CGCM1) to much more than observed (ECHAM4), and have varying skill at simulating ENSO (IPCC, 2001a, pp. 499–504).

A simple estimate of future climate change can be obtained using a simple CO_2 regression model derived by comparing 20th century PNW temperatures with global CO_2 (see Appendix), and projecting forward with a 1%/year CO_2 increase (Figure 4b). This procedure leads to a constant warming rate of 0.40 °C/decade from 2000–2050. The climate models (Figure 4c, Table I) produce comparable rates of warming, averaging 0.45 °C/decade, and even in the coolest scenario the region sees substantial warming. However, the models with control runs before the 1990s all have late-20th century rates of warming that are faster than observed (i.e., their lines lie above the observed curve in Figure 4c).

Nearly all of the scenarios include wetter winters and only small changes in absolute summer precipitation, with the result that annual precipitation increases modestly (Table I); the precipitation changes lie well within the 20th century range of year-to-year variability. The small summertime precipitation increases projected by some models do not change the fundamentally dry summers of the Northwest, and do not ameliorate the increased drying of the soil column brought by higher temperatures (Hamlet and Lettenmaier, 1999). Note that confidence in models' simulation of precipitation is much lower than confidence in simulation of temperature (IPCC, 2001a, p. 482), and that the use of several models gives a broad spread in decadal averages in part because of model interdecadal variability; for example, the HadCM2 model has vigorous interdecadal variability and in this simulation the 2020s happen to be a wetter decade than any other between 1900 and 2070.

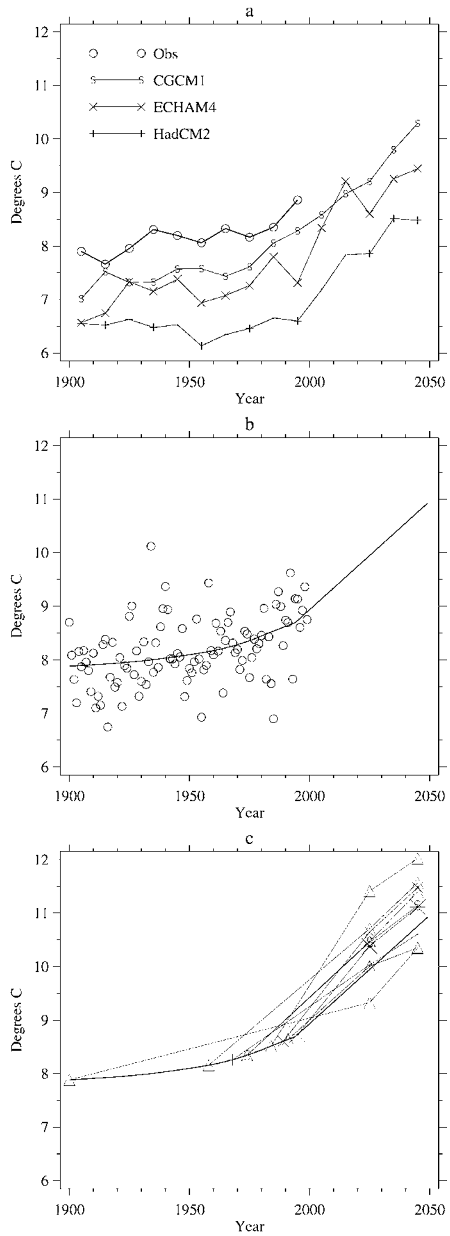

Figure 4. Observed and modeled temperature over the Pacific Northwest. (a) Ten-year averages of observed temperature, 1900s–1990s, and simulated 10-year average temperatures for 1900s–2040s for the Pacific Northwest calculated by three climate models. (b) Observed PNW temperatures (individual years shown as circles) and long-term trend fitted by regression of PNW temperatures on CO_2. (c) CO_2-derived curve from (b) and changes from each model's control run to the 2020s and 2040s for eight climate models. For each climate model, the 21st century changes are keyed as indicated by the lines to the year in which observed CO_2 values matched the value used in the control run; see Appendix for details.

Table I
Changes in PNW climate from eight climate models for the 2020s and 2040s

	Temperature change	Precipitation change	
	Annual	Oct–Mar	Apr–Sep
2020s			
Low	0.5 °C (HadCM3)	+2% (PCM)	–4% (HadCM3)
Average	1.5 °C	+8%	+4%
High	2.6 °C (CCSR)	+18% (HadCM2)	+14% (HadCM2)
2040s			
Low	1.5 °C (PCM)	–2% (ECHAM4)	–7% (ECHAM4)
Average	2.3 °C	+9%	+2%
High	3.2 °C (CCSR)	+22% (CGCM1)	+9% (CSIRO)

3. Water Resources

3.1. BACKGROUND AND INFLUENCE OF MEAN CLIMATE

Fresh water is a crucial resource in the Northwest, and climatic effects on water resources strongly influence many other natural resources, notably salmon and forests. The sharp variations in precipitation through the course of the year (Figure 3) and across the spatial extent of the region produce enormous differences in freshwater availability. Most of the region receives less than 50 cm of precipitation a year, and dry summers make freshwater a limiting resource for many ecosystems and human activities. Despite the large number of dams in the Northwest, the regional infrastructure relies heavily on snowpack to transfer water from the wet winters to the dry summers, making the region especially vulnerable to a warming climate with less snow. Furthermore, water supply, availability, and quality are already stressed by many growing demands.

The seasonality of stream flow is generally quite different west and east of the Cascades, with the typical west-side river peaking in winter because of rainfall, and the typical east-side river peaking in late spring because of snowmelt. The Columbia River, which is dominated by snowmelt, is one of the nation's largest, draining roughly three-quarters of the region (Figure 1) and carrying 55–65% of its total runoff. Because its watershed is so large, the Columbia's flow reflects an averaging of weather conditions over large areas and seasonal timescales. Consequently, climatic effects on its flow can be detected and projected with more confidence than for smaller river systems, especially rain-dominated rivers, which respond most strongly to shorter-term and more local precipitation events.

The Columbia is the region's primary source of energy and irrigation water, and is managed by multiple agencies for multiple, often conflicting, values, including hydroelectricity production, flood control, fish migration, habitat protection, irrigation, navigation, recreation, and municipal and industrial water supply. Agriculture takes the largest share of present withdrawals for consumptive use, especially in Idaho. Other demands are growing, in particular, the recent demand for in-stream flow requirements to protect salmon. With more than 250 reservoirs and 100 hydroelectric projects, the Columbia system is among the most developed in the world and has little room for further expansion, even as changing priorities are intensifying competition for water. The high level of development has substantially altered the flow regime, smoothing out the sharp late-spring peak and raising streamflow during the fall and winter. Without this unnatural flow regime, current hydropower and flood control objectives cannot be met.

3.2. SENSITIVITY TO CLIMATIC VARIATIONS, INCLUDING ENSO AND PDO

Because much of the annual flow on the Columbia River originates as snow, the Columbia has a long memory for climatic conditions during the preceding winter. We calculated correlations and regressions between monthly climate anomalies and monthly streamflow anomalies in the Columbia River (partial results are shown in Figure 5). From November to May, temperature anomalies have a significantly positive correlation with flow in the same month, because warmer weather melts low-elevation snow and increases the fraction of precipitation falling as rain, increasing streamflow. From February to July, however, temperature anomalies have a significantly negative correlation with flow in summertime (June–September), since a warm spring brings early melt, leaving less snow available to provide high streamflow in summer.

Although spring temperatures influence the Columbia for a few months, *precipitation* influences the Columbia even longer. Precipitation in October through April has significant positive correlations with streamflow up to 11 months later. In fact, the largest influence on streamflow during the high-flow months comes from precipitation in January, with a somewhat smaller influence from spring temperatures.

It follows that Columbia River streamflow shows a strong correlation with both ENSO and PDO. These oscillations favor combinations of temperature and precipitation (warm and dry or cool and wet) that interact to produce large anomalies in snowpack and streamflow, and hence on regional water supply. On average, warm-phase years see lower accumulation of snowpack, earlier shift from snow accumulation to melting and average annual flow in the Columbia about 10% below average, with larger reduction of peak flow in June (Figure 6; Figure 3, third row). The effects of ENSO and PDO are nearly additive, so years with both in their warm phase have brought the lowest snowpack and streamflow, and the highest incidence of droughts. Five of the six extreme multi-year droughts since 1900 occurred during

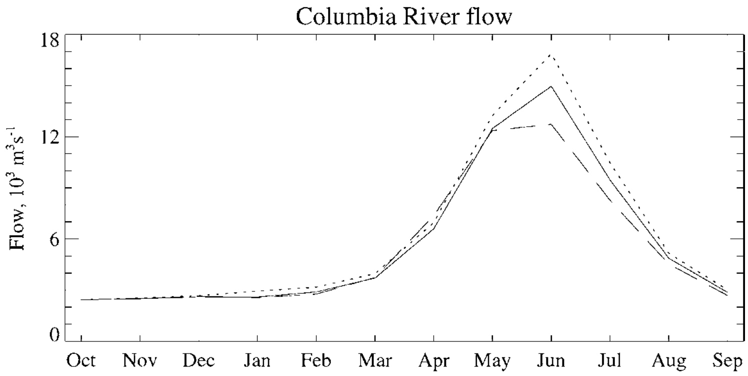

Figure 5. Sensitivity of Columbia River flow to monthly climatic variations. Monthly mean flows are indicated by the solid line, response to April temperature $+1\sigma$ anomalies by the dashed line, and to January $+1\sigma$ precipitation anomalies by the dotted line. Response to anomalies is calculated by regressing monthly mean flow for each month on monthly mean temperature or precipitation for each month. Flow in May, June, and July is most sensitive to precipitation anomalies in January and to temperature anomalies in April.

the warm phase of PDO (Mote et al., 1999b, p. 32). Four of the five highest-flow years recorded occurred when PDO was in its cool phase (three of them when ENSO was also in its cool phase), and flooding is likeliest in such years. When ENSO and PDO are out of phase, streamflow tends to be near its long-term mean. As shown in Figure 3 (fourth row) for the Cedar River, which supplies much of the municipal water to the urban Seattle area, the effects of ENSO and PDO are similar on both sides of the Cascades.

3.3. IMPACTS OF FUTURE CLIMATIC CHANGES

Simulations using a detailed hydrological model (VIC, for Variable Infiltration Capacity) of the Columbia River Basin in a warmer climate projected widespread loss of moderate-elevation snowpack, as Figure 7 shows. Even with the modest warming projected for the 2020s, substantial areas of low-elevation snow are lost. By the 2040s, the pattern of snow in any given month during the snowmelt period is projected to be similar to present snowcover a full month later. These results are broadly in agreement with similar results for the PNW (Leung and Ghan, 1999a,b) and elsewhere in the American West (Giorgi and Bates, 1989; Giorgi et al., 1994).

On snowmelt-dominated rivers like the Columbia, the very likely effect of these linked changes in temperature, precipitation and snowpack will be to increase winter flow and decrease summer flow (Figure 8). Winter flow increases both because there is more winter precipitation and because more of it falls as rain; summer flow decreases both because there is less snowpack and because it melts earlier in the spring. Both precipitation and temperature matter. When changes in temperature and precipitation are considered separately, temperature – which climate models project with greater confidence than precipitation (IPCC, 2001a, p. 482) – has

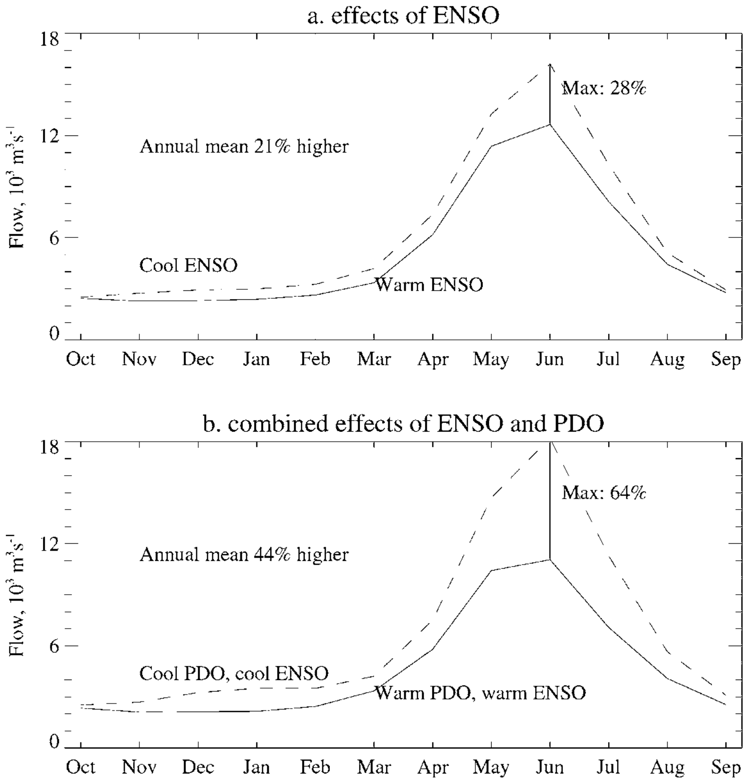

Figure 6. Mean Columbia River flow at The Dalles (naturalized; see appendix) for ENSO and PDO phases indicated.

the larger effect on crucial summer streamflows (Mote et al., 1999b, Figure 28). The pre-eminence of temperature in determining shifts in flows comes not just from the numerical results with the VIC model but also from the simple analysis presented in Figure 5 together with the projected changes shown above in Table I. A one-standard-deviation (1-σ) anomaly in spring temperature changes June–July streamflow by about the same amount as an opposite 1-σ anomaly in winter precipitation, but the climate model projections are for changes in temperature that far exceed 1-σ whereas the projected changes in precipitation are only a small fraction of a standard deviation. In short, for the precipitation and temperature changes projected by the climate models, the temperature changes are likely to be far more important because they shift flow from summer to winter.

To assess the socioeconomic effects of these changes in stream flow, a reservoir operations model (ColSim; see Hamlet and Lettenmaier, 1999; Miles et al., 2000) was used to project how climatic change affects the reliability of different water-management objectives. Reliability is defined as the observed (or simulated) probability of meeting an objective in any month: if an objective is met in 96 out of 100 months, the reliability is 96%. ColSim was first used to examine how ENSO

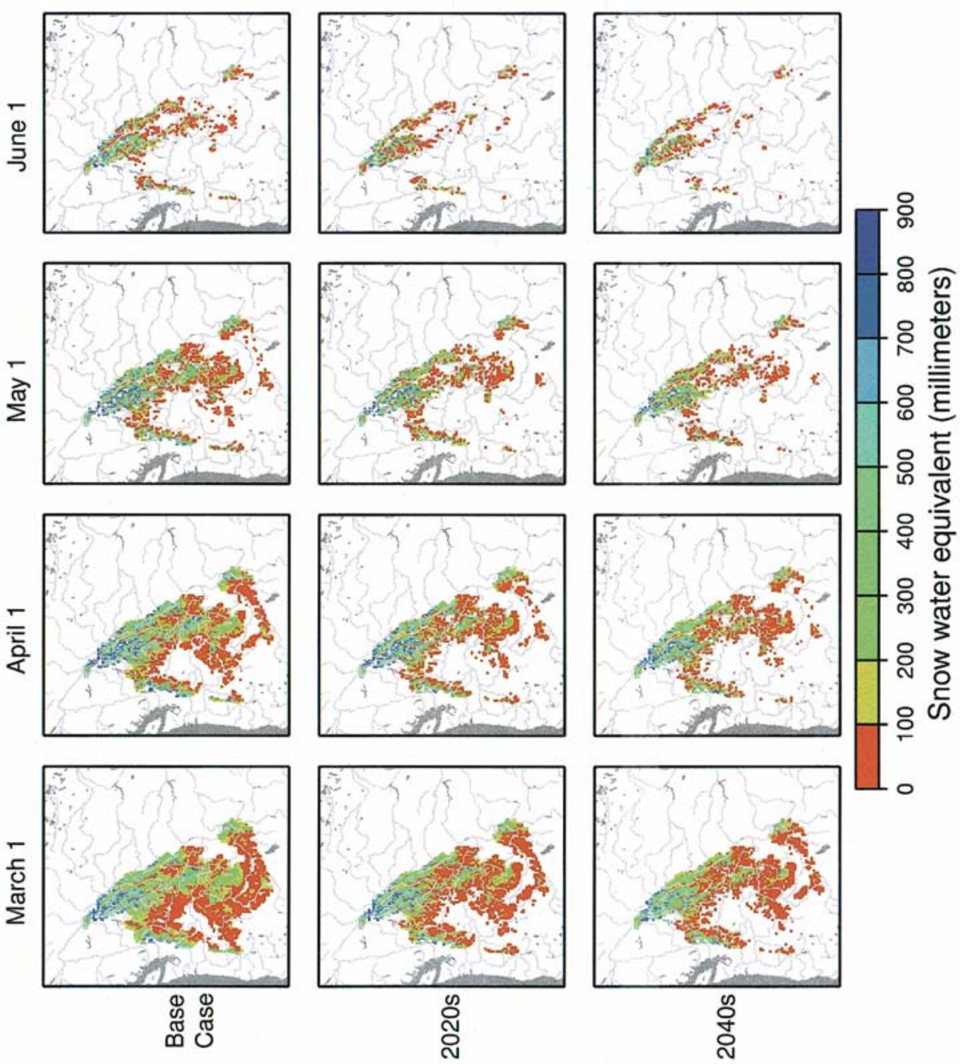

Figure 7. Projected changes in Columbia Basin spring snowpack (in mm of snow water equivalent) for 20th century climate, 2020s, and 2040s, using the VIC hydrology model driven with a climate-change scenario derived by averaging climate changes from simulations with the HadCM2, HadCM3, PCM, and ECHAM4 climate models.

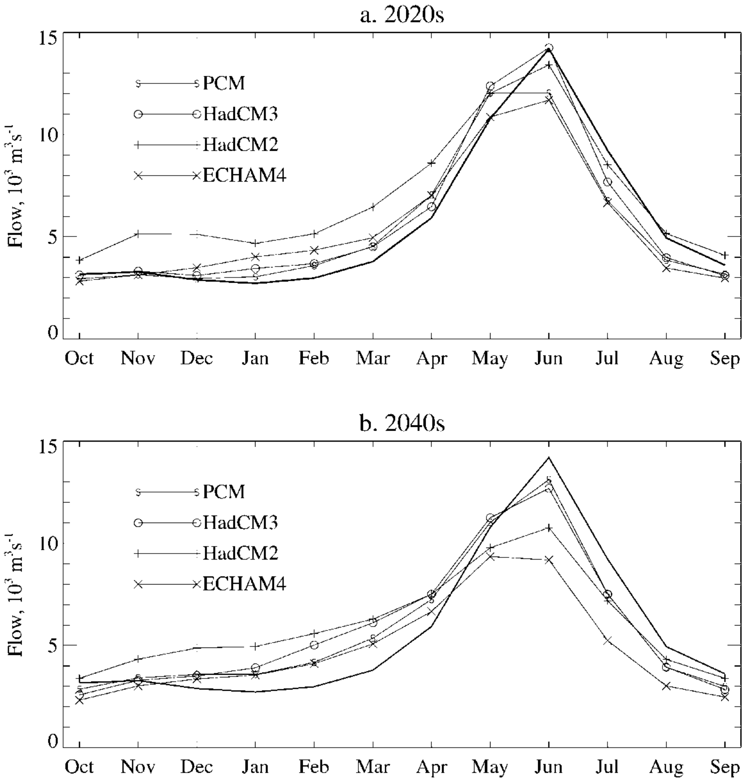

Figure 8. Columbia River streamflow at The Dalles, observed (bold) and projected for the 2020s and 2040s using the VIC hydrology model for ECHAM4, HadCM2, HadCM3, and PCM climate scenarios.

and PDO affect reliability of six uses, under two different sets of system operation rules: 1995-era rules, under which the practice is to grant highest priority to ensuring flood control and availability of winter hydroelectric energy sold on 'firm' contracts with some instream flow requirements for fish,⋆ and a set of alternative, 'fish-first' rules that would give highest priority to maintaining minimum flows to protect fish. Although a 'fish-first' operating system is unlikely to be implemented, this calculation demonstrates that the system can successfully insulate one or two objectives from climatic variability (e.g., flood control and hydropower for the 1995-era rules, or flood control and fish flows under the 'fish-first' system). The effect of alternative operation rules for the system is to re-distribute risks of shortage among uses. The results show that reliability is high for all objectives in cool PDO/La Niña years (which tend to have higher than average flow; see Figures 3 and 6) and that *one top-priority objective can be maintained at or near 100% reliability*

⋆ Despite recent policy changes to protect salmon, firm energy contracts still receive highest priority in practice, and insufficient reservoir capacity is allocated to increase late-summer flows for fish.

even in warm PDO/El Niño years (which tend to have lower than average flow), but that other uses suffer large reliability losses in low-flow years. For example, the reliability of both the fish-flow objective under present rules, and the firm energy objective under 'fish-first' rules, falls to about 75% in warm PDO/El Niño years (Figure 32 of Mote et al., 1999b; Miles et al., 2000). Other operating policies might offer different tradeoffs. Of the six objectives considered, the most sensitive to low flow under the current operating system were fish flows and recreational demand for full summer reservoirs, which both drop below 85% reliability when annual flow is only 0.25 standard deviations below its mean, a condition that could occur as often as four years out of ten (Mote et al., 1999b, pp. 39–41).

For future conditions like those shown in Figure 8, projections of changes in reliability for six objectives under present operational rules, using two climate models for the 2020s, are shown in Figure 9 (Hamlet and Lettenmaier, 1999; Cohen et al., 2000). Under present rules, reliability of firm energy is projected to remain near 100%, while other uses suffer reliability losses up to 15%. With the sharp increase in precipitation in the HadCM2 for the 2020s, reliability of non-firm energy and summer irrigation rises significantly but flood control becomes more problematic. Even for the drier ECHAM4 scenario, the changes in reliability for the 2020s are only 2–6%. Lower summer streamflow in the 2040s bring significant reductions in reliability, especially with the warm-dry ECHAM4 scenario. The changes in reliability are not proportional to changes in summer flow: e.g., for ECHAM4 in the 2040s, the natural flow reduction is about 40% in June–July–August, much larger than the reductions in reliability for objectives that depend on flow in these months. The simulated changes in reliability also suggest that despite reductions in natural storage, the system can partially mitigate the effects of these changes in streamflow variability by using the existing reservoir storage to transfer water from winter to summer.

In the PNW river basins we have examined, the largest impacts stem not from the changes in total annual flow (which, for the 2020s, range from –6% to +22%) but from changes in flow during certain seasons. Unregulated smaller, rainfed and mixed rain/snow streams west of the Cascades are already susceptible to winter flooding, especially in the wetter winters of La Niña years (Mote et al., 1999b, Table 4). Projected warmer, wetter winters suggest further increases in the risk of winter flooding in these basins, and continuing growth in population and infrastructure near rivers may also increase the property vulnerable to such flooding. Detailed assessments of this risk, and its potential consequences for property damage and human health, have not yet been conducted but should be a high priority.

As mentioned earlier, large reductions in summer flow are likely in smaller river basins with a relatively large portion of their catchments near the current mid winter snow line, even if their total annual flow increases. Water supply systems with higher storage to flow ratios may be relatively robust to such changes in streamflow (since winter runoff can be captured), whereas systems with limited storage are potentially more vulnerable.

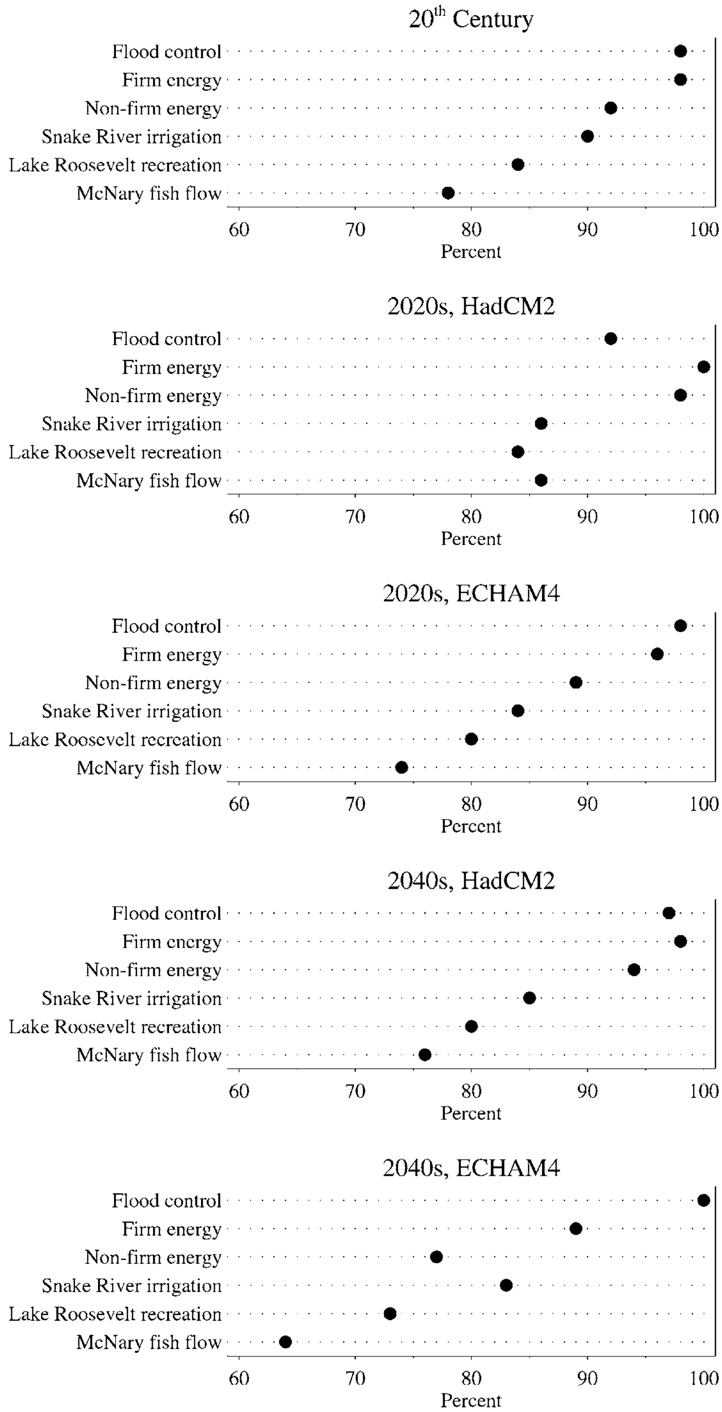

Figure 9. Reliability (%) of various Columbia management objectives for current and future climate, assuming present operating rules. See Miles et al. (2000) for definitions of objectives.

In large, snowmelt-dominated systems like the Columbia, simulations suggest that there is little increased risk of flooding because spring peak flows are not expected to increase much (Figure 8) and because the management system is adequate to respond to floods. The Columbia's water resources are believed to be much more strongly influenced by changes in low flows both because of limited reservoir storage and institutional considerations (Callahan et al., 1999; Miles et al., 2000). Reduced summer flows are likely to reduce both summer hydropower resources and irrigation water supplies by mid-century, exacerbating already-sharp allocation conflicts between consumptive use for irrigation, increasing priority for maintaining instream flow for fish habitat, and (west of the Cascades) population growth with its increased demand for energy and water for municipal and industrial use.

Increasing supply-side stresses on the water resources systems on the west side of the Cascades are likely to coincide with increased water demand stemming from population growth but also induced by climatic change itself; lawns and irrigated crops use more water in a warmer summer. For example, an analysis of the impacts of climate change on Portland's municipal water supply for the 2040s (Palmer and Hahn, 2002) projected that a warming of about 2.0 °C would decrease annual minimum storage (a measure of water supply system performance) by about 1.3 billion gallons, and would increase demand by 1.5 billion gallons. Population growth is currently estimated to increase demand in the 2040s by 5.5 billion gallons (ibid.), only moderately larger than the combination of changes in supply and demand resulting from climatic change.

4. Salmon

4.1. BACKGROUND AND INFLUENCE OF MEAN CLIMATE

Salmon (*Oncorhynchus spp.*) are anadromous fish, meaning that they swim up rivers and streams to spawn after spending most of their adult lives at sea. After hatching, young salmon remain in the stream for a few weeks to several years, depending on the stock, then swim downstream to the ocean. In the ocean the salmon grow to adulthood and live for several months to six years before returning to their spawning grounds. Among these species are a large number of genetically and behaviorally distinct populations, or stocks, which have evolved to take advantage of various niches, in part by pursuing different migration strategies. The diversity of behavior leaves different stocks sensitive to environmental conditions (including climate-driven conditions) in different ways, thereby buffering the genus as a whole against a catastrophic population crash (National Research Council, 1996).

Different stocks have fared quite differently in the 20th century under stresses imposed on them by humans and other factors. Most Northwest salmon stocks have been highly stressed by commercial fishing (recently curtailed) and by threats to their stream habitats including urbanization, sedimentation and pollution of streams, changes in streamside vegetation, erosion due to land-use practices like clear-cutting and road building, and draining of wetlands. Construction of dams has harmed salmon in many ways, reducing the quantity and quality of habitat by blocking passage and by changing free-running rivers into chains of lakes, warming in-stream temperatures, reducing dissolved oxygen, and altering sediment loads and other aspects of the aquatic environment. In addition, wild salmon face intense competition from hatchery fish, which in some areas are being released in far greater numbers than natural smolt migrants are produced (Palmisano et al., 1993).

Over the past century, Pacific salmon have disappeared from about 40% of their historical breeding range in Washington, Idaho, Oregon, and California, and many remaining populations are severely depressed (National Research Council, 1996). The decline is not universal: the populations that have fared the best are from coastal rather than interior streams, or from more northerly ranges, and have relatively short freshwater rearing periods.

Mean climate plays several important roles in shaping the interaction between salmon stocks and their environment. First, prolonged exposure to stream temperatures at and above 21 °C is lethal for most adult salmon (McCullough, 1999). This thermal limit helps determine the geographic range of salmon; some salmon species (chinook, coho) are found as far south as California, while others are generally confined much farther north. Second, the timing of the spring freshet plays an important role in the oceanward journey of many juvenile salmon. Third, in the spring the coastal winds undergo a seasonal reversal in direction from mostly southerly to mostly northerly, and the northerly winds are responsible for driving ocean upwelling that provides nutrients for the entire food chain, in which adult salmon are near the top but juveniles are not. Mean climate also determines productive regions in the ocean, partly through seasonally varying wind-driven circulations.

4.2. SENSITIVITY TO CLIMATIC VARIATIONS, INCLUDING ENSO AND PDO

Salmon are sensitive to various climate-related conditions, both inshore and offshore, at various times of their life cycle. Incubating eggs are vulnerable to stream scouring from floods. Migrating juveniles are probably most sensitive to climate when they reach salt water because they must avoid new predators (sea birds, marine mammals, and other fish) and because they require food immediately on reaching the ocean (Pearcy, 1992). Their fate is sensitive to the timing of their arrival relative to the onset of spring upwelling and spring phytoplankton bloom, as well as the behavior of predators and competitors. This relative timing in turn relies on a host of environmental factors that together can determine the survival rate of a year-class of salmon, including not only the timing but also the character of upwelling winds (highly variable winds produce more upwelling) and the circulation and stratification of the upper ocean, which is strongly influenced by winter climate (Logerwell et al., 2003). The sensitivity of salmon to conditions in the open ocean cannot yet be described, because there is insufficient evidence concerning the interaction of salmon with their open-ocean environment.

Productivity of salmon stocks throughout the Northeast Pacific show a strong 'seesaw' association with PDO (Figure 10) (Mantua et al., 1997; Hare et al., 1999; Hare and Mantua, 2000), although it is not yet possible to disentangle the effects of various inshore, offshore, climatic, and non-climatic factors. Salmon stocks in the Northwest are generally more abundant in the cool PDO phase and less abundant in the warm phase, while Alaska salmon show the opposite pattern and British Columbia stocks are mixed. The mechanisms for this observed climatic effect on stocks are poorly known, and probably include some effects of both freshwater and marine changes. One likely mechanism is that coastal waters off Washington and Oregon during the warm phase are warmer and more thermally stratified, and consequently poorer in nutrients. The PDO signal is much weaker for Puget Sound salmon than for stocks that exit directly from rivers into the open ocean, suggesting that the gradual increase of salinity experienced by juveniles passing through an estuarine environment may increase their resilience for reasons unknown (Pinnix, 1998).

Behind this simple seesaw notion lie a number of complexities. First, salmon abundance is equated here and generally with catch, which (one might suspect) could reflect a host of factors besides abundance, like fishing effort. However, catches are a good indicator of stocks, because catch variation between the 1930s and mid-1990s was almost entirely due to stock fluctuations, not variation of fishing effort (Beamish and Bouillon, 1993). Second, although ENSO and PDO have similar effects on ocean and terrestrial environments in the Northwest, the signal of PDO in salmon stocks is much stronger than that of ENSO, suggesting that the mechanism involves persistent conditions over several years. This is apparent in the bottom row of Figure 5, which was composed using an annually varying index of PDO (with the climatic data lagged to correspond to the year of juvenile coho ocean entry; the results are similar when calculated as averages over PDO phases). Third, some species and subspecies respond to PDO not at all, or even oppositely to the coho shown here (Hare and Mantua, 2000). For example, chum salmon in Washington were more plentiful during warm phases than cool phases of PDO.

Nonetheless, the picture that emerges when salmon data and climatic data are taken together is that persistent warm-phase PDO has favored salmon abundance in Alaska and has diminished salmon abundance in the Northwest. Working out the details of this influence is a difficult but important challenge for understanding how anthropogenic climate change will affect salmon in the future.

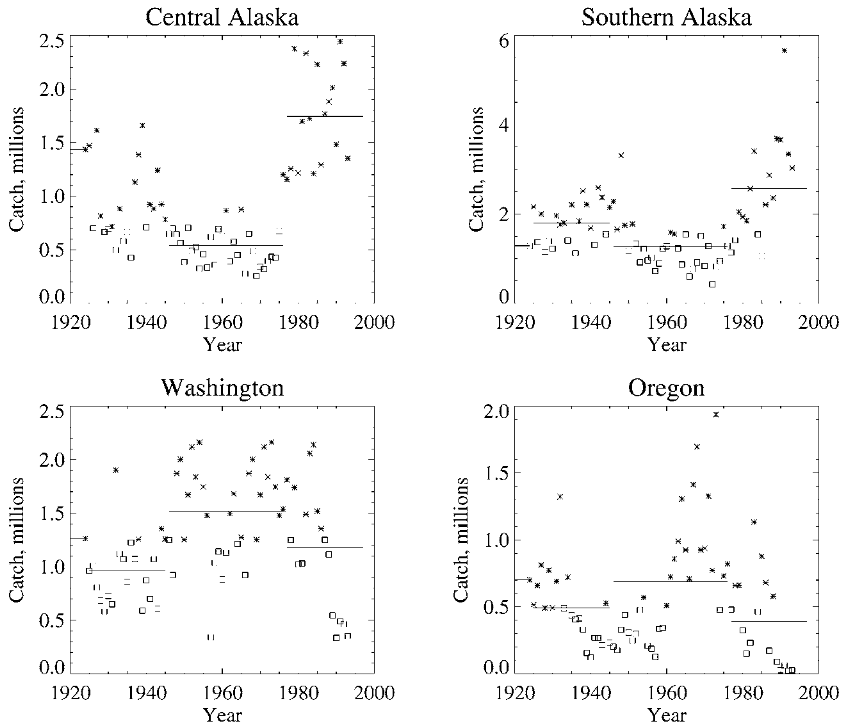

Figure 10. Catches of Northwest and Alaska coho salmon stocks for each year from 1924 to 1993. For each salmon stock, years with below-median catch are shown as boxes and those above-median catch are shown as stars, and average catch over successive PDO phases is shown as horizontal lines. During warm phase PDO, Alaskan catches tend to be high and Northwest stocks tend to be low; the oppositive is true during the cool phase.

4.3. IMPACTS OF FUTURE CLIMATIC CHANGES

Climate models presently lack the detail to project changes in many specific environmental factors that are most important for salmon, such as the timing of seasonal coastal upwelling, variations in coastal currents, and vertical stability of the water column. But where climate models are informative, their projections for PNW salmon are largely unfavorable. Increased winter flooding in certain streams, reduced summer and fall flows, and warmer stream and estuary temperatures are all likely and are all harmful for salmon. If outward migration patterns of wild juveniles change, whether because warmer streams make them mature earlier or because freshets occur earlier, then the ocean and estuary conditions they find upon arrival might not match those they have evolved to exploit. The strength and seasonality of upwelling appears unlikely to change in a warming climate (Mote and Mantua, 2002).

In the open ocean, projections of the future environment of salmon is in one sense easier – sea-surface temperatures are a simple and universal output of climate models – but our lack of understanding of how the ocean environment influences salmon health and survival makes the impacts of these projected changes on salmon ambiguous. One study (Welch et al., 1998) examined the distribution of sockeye salmon (*O. nerka*) and coincident SST data; sockeye salmon distribution fell within a boundary delineated by a seasonally varying isotherm of SST that was always considerably cooler than their known physiological thermal limits. Welch et al. (1998) interpreted these catch data as implying a lower thermal limit due to metabolic constraints, and posited that oceanic warming from even a doubling of CO_2 (very likely in the 21st century; IPCC, 2001a) may push the range of some salmon north out of the Pacific entirely. An alternative interpretation of the catch data is that the boundary was caused not by SST but by some other important factor like distribution of prey, and indeed recent studies suggest that the notion of direct ocean thermal limits to salmon survival may be too simplistic (Walker et al., 2000). Data from temperature-recording tags show that salmon move hourly and daily through wide temperature ranges, presumably by moving between surface and deep waters; this result, and high-seas sampling of salmon, suggest that the effect of ocean temperature on salmon is not only direct, but operates through changes in both food supply and metabolic rates (Pearcy et al., 1999; Walker et al., 2000). Therefore, a modest warming might not lead to dramatic changes in ocean habitat unless it also causes changes in other parts of the massive food web.

Salmon are already beset by a long list of human-caused problems, to which climatic change is a potentially important addition. The effects of future climatic trends, and their potential to interact with other stresses, are not known. Neither is the extent to which current and proposed measures to protect salmon by restoring stream habitat and changing dam operations will restore depleted stocks and increase their resilience to climatic stresses. Indeed, predicting stock-by-stock salmon abundance is a difficult challenge even on a one-year timescale. The effects of climatic change will probably bring less favorable environmental conditions to most Northwest salmon stocks, but it is impossible to say broadly (let alone for specific stocks) how those changes will compare with other environmental changes they have faced and will face.

5. Forests

5.1. BACKGROUND AND INFLUENCE OF MEAN CLIMATE

Evergreen coniferous forests cover much of the landscape of the PNW. In the maritime region west of the Cascade crest, the forest zone extends from sea level to the upper tree line at 1500–1700 m above sea level, where tree establishment and growth are limited by typically late snowmelt and short growing seasons (Franklin et al., 1971; Peterson and Peterson, 2001). In the drier climate east of the Cascade crest, forests have both a high-elevation and a low-elevation tree line. The lower tree line occurs where warm summer temperatures and low annual precipitation combine to produce late-summer soil water deficits. Near this lower tree line, trees often grow at low densities in savannas or open forests. With increasing elevation, temperatures decline and annual precipitation increases, reducing soil water deficits and allowing closed-canopy forests to develop.

Tree establishment, growth, and survival within the forest zone may be limited by one or more environmental factors that vary spatially with climate, topography, and soils. Climatic influence is especially strong at forest margins and at the beginning of a tree's life. Drought-tolerant species like ponderosa pine (*Pinus ponderosa*) dominate forests and savannas near the lower (dry) tree-line on the east slopes of the Cascades, while cold- and snow-adapted species like subalpine larch (*Larix lyallii*) dominate forests near the upper tree line. In the middle forest zone on the dry east side and the lower forest zone on the wet west side, reduced environmental stress allows more productive forests to develop, and species composition is strongly influenced by shade tolerance and competitive interactions.

Summer moisture deficits resulting from the dry Northwest summers (Figure 2) influence forests in several ways. In the drier interior, forests experience more severe summer soil-moisture deficits, the length and intensity of which control species distributions and forest productivity (e.g., Zobel et al., 1976). The dry period hampers seedling establishment and summer photosynthesis, but mature conifers in the Northwest tolerate moisture deficits because they are deep rooted (up to 24 m in ponderosa pine; Stone and Kalisz, 1991). The summer dry period also creates favorable conditions for insect outbreaks and fires (Agee, 1993). In the western, maritime forests, evergreen conifers compensate for reduced summer photosynthesis by shifting a greater proportion of production and growth to the cooler fall, winter, and spring months, when soil water and nutrients are more available (Waring and Franklin, 1979).

Fire is an important natural disturbance in northwest forests, although natural fire regimes vary substantially within the region. In cold high-elevation forests and wet western forests, short summer dry periods and high mean fuel moisture levels produce very low fire frequencies. However, high fuel accumulations and forest densities create the potential for fires of very high intensity and severity, often leading to complete stand replacement, when fuels are dry. In dry interior forests near the lower treeline, the longer summer dry period produces natural fire regimes with high-frequency, low-intensity fires. These high frequency fire regimes maintain open stand conditions by killing seedlings and saplings before they develop fire resistance and promote low fire intensities by consuming fuels and preventing high fuel accumulations. Decades of fire exclusion in these low elevation interior forests have allowed fuel accumulations and forest densities to increase to the point that fire intensity is often much higher than in the past and, as in the wetter and cooler forests, often leads to complete stand replacement rather than merely suppressing understory trees.

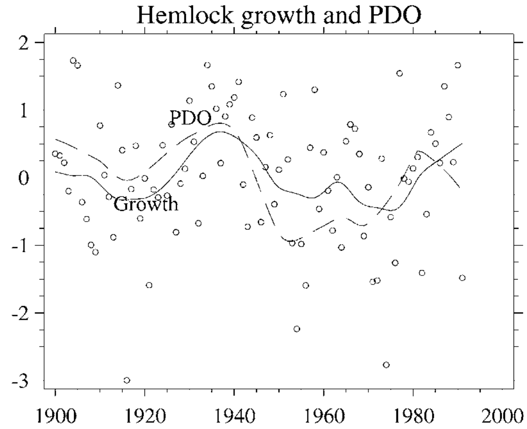

Figure 11. Annual growth of high-elevation mountain hemlock (first principal component of growth rings from 515 trees; see Peterson and Peterson, 2001) compared with the PDO index. Both time series have been smoothed using the loess algorithm (Cleveland, 1993) with a roughly 20-year smoothing window; the annual data are shown only for tree growth.

5.2. SENSITIVITY TO CLIMATIC VARIABILITY, INCLUDING ENSO AND PDO

Effects of climatic variability on tree growth and forest productivity are often most pronounced in forests near the lower tree line, which are typically sensitive to variations in annual precipitation, and in forests near the upper tree line, which are sensitive to variations in winter precipitation, spring snowpack depth, and summer temperature (Peterson and Peterson, 1994, 2001). Analysis of tree-ring records from subalpine fir and mountain hemlock (*Tsuga mertensiana*) forests showed that in much of the PNW high-elevation forest productivity is anticorrelated with spring snowpack depth, and correlated with the PDO (Figure 11; see Peterson and Peterson, 2001). Near the lower treeline, growth is negatively correlated with PDO, because the warm dry winters typical of positive-PDO periods reduce snowpack, increase summer drought stress, and reduce growth (Little et al., 1994; Peterson, 1998).

Reduced snowpack associated with warm-phase PDO periods is also favorable for seedling establishment in many subalpine meadows and may promote upward expansion of tree lines (e.g., Franklin et al., 1971; Little et al., 1994). Similarly, later snowmelt associated with cool phase PDO appears to be important for seedling establishment on drier sites, where well-developed root systems are required for seedlings to survive soil moisture deficits during drier years (Woodward et al., 1995). In general, decadal variations in climate appear to be important for allowing trees to become established in otherwise stressful habitats. Once well established, trees are better able to endure these stresses.

In other regions, such as intermediate elevation stands in the interior, and Douglas-fir, western hemlock (*Tsuga heterophylla*), and Pacific silver fir (*Abies amabilis*) forests west of the Cascade crest, the effects of climatic variability are less clear. In these stands, competition and other factors obscure present climatic signals in individual trees (Brubaker, 1986; Dale and Franklin, 1989).

Climatic variability can influence forest structure and composition by influencing the frequency, severity, and extent of damage from fires, insect infestations, and disease. Major disturbances reset forests to their establishment stage, when trees are the most sensitive to adverse environmental conditions. Area burned by wildfire shows a connection with atmospheric circulation patterns from May to August (Gedalof et al., 2003), patterns that are different for different parts of the region. For insect and disease mortality, the available 20th-century data are inadequate to quantify the region-wide effects of climatic variability, but smaller-scale studies have shown strong correlations of both bark beetle and defoliator outbreaks with severe drought conditions (Swetnam and Lynch, 1993).

A review of modern records of annual area burned by fire in Northwest forests suggests a possible association between the total annual area burned and phase of the PDO, particularly before the introduction of widespread fire suppression (Mote et al., 1999a). For example, the warm-PDO period of 1925–1945 had much more area burned than the cool-PDO periods immediately preceding and following it, although this result may be confounded by improvements in fire suppression methods during the 1940s. A relationship between PDO and forest fire activity is likely because the annual area burned is also positively correlated with regional drought, as measured by the Palmer Drought Severity Index (PDSI) and the PDSI is correlated with PDO (ibid.). Effects of ENSO on fire regimes are less clear. Unlike the strong ENSO influence on wildfires in the Southwest U.S. (Swetnam and Betancourt, 1990), our analysis reveals no region-wide effect of ENSO although a subtler ENSO influence is possible.

5.3. IMPACTS OF FUTURE CLIMATIC CHANGES

Two elements of future climatic change scenarios are likely to be particularly important for PNW forests. Warmer winter and spring temperatures are expected to reduce winter snowpack accumulations, shift the winter snowline to higher elevations, and melt snow earlier in the spring. Warmer summer temperatures are expected to increase evaporative demands, which may or may not be offset by higher winter and spring precipitation. Forest responses to these climate-driven environmental changes will undoubtedly vary spatially across topographic and climatic gradients, vary temporally with continued annual and decadal climatic variability, and vary among species with different physiological traits. Computer simulation models, gradient studies, and experimental results offer some insights into likely forest responses and the major sources of uncertainty.

The effects of reduced snowpack will vary among sites. On high-elevation sites, earlier snowmelt should promote higher rates of seedling establishment in subalpine and alpine meadows and increase subalpine forest productivity (Figure 11) by extending the growing season (Peterson, 1998; Peterson and Peterson, 2001).

In general, the upper treeline could rise considerably at some sites, with increased dominance of species such as subalpine fir that tolerate lower soil moisture during the summer (Zolbrod and Peterson, 1999). On somewhat drier high-elevation sites, however, the longer growing season could allow summer soil moisture deficits to develop as trees deplete soil moisture earlier. At lower elevations, reductions in snowpack reduce the amount of winter precipitation that is stored for soil water recharge in the spring and could increase the severity and duration of summer soil moisture deficits, reducing growth and increasing the risk of fire (Mote et al., 1999a).

Throughout the region, warmer summers without substantially higher summer rainfall would increase summer soil moisture deficits (Hamlet and Lettenmaier, 1999) and tree stress, and reduce net photosynthesis, tree growth, and seedling survival for many tree species. Forests rely on deep soil water throughout the summer when surface soils are often dry. Increased winter precipitation could increase soil recharge on sites that currently do not reach field capacity. There are indications, however, that many forest soils below the snow line in the Cascade Range are already fully recharged by winter rains, so some additional winter precipitation may be lost as runoff (Harr, 1977; Jones and Grant, 2001).

With warmer temperatures, forests may begin growing earlier in the spring and may benefit from increased soil water availability and reduced evaporative loss in that season. Elevated CO_2 concentration may also, at least over the short-term, mitigate productivity losses from summer drought stress, by increasing tree water-use efficiency through increased photosynthetic efficiency or reduced stomatal conductance (e.g., Bazzaz et al., 1996). Conifers at high-elevation sites and low-elevation, maritime sites in North America have significantly increased growth since 1850 (McKenzie et al., 2001), corroborating (for high-elevation forests) previous studies in western North America (e.g., Peterson, 1998). This growth increase *is not* related to temperature and *is* correlated with the rate of CO_2 increase, although a cause-effect relationship cannot be demonstrated.

Process-based models are needed to represent and quantify these effects, because empirical studies can observe forest responses only to the present range of climatic conditions with present CO_2 concentration (VEMAP Members, 1995). Even with assumptions of increased water-use efficiency, ecological models driven by the HadCM2, CGCM1, and other climate-change scenarios project that cool coniferous forests in the western part of the region will contract, with reductions in vegetation carbon or leaf area exceeding 50% in some areas and replacement by mixed temperate forests over substantial areas. Dry forests in the eastern part of the region are projected to expand in response to increased winter precipitation, with increases in vegetation carbon or leaf area also exceeding 50% in some locations (Neilson and Drapek, 1998; Daly et al., 2000). The increases in the east are relative to a smaller current biomass, and so are smaller in absolute terms. The magnitude and consequences of future changes in water-use efficiency associated with elevated CO_2 are uncertain in projecting the climatic response of Northwest forests over the next century. While the balance of preliminary evidence suggests a small water-use efficiency increase in Northwest coniferous forests due to enhanced CO_2, model results differ substantially about the importance of CO_2 for the extent, density, and species distribution of Northwest forests. Over the longer term, in some forests increased evapotranspiration under warmer temperatures could outweigh increased water-use efficiency (Bachelet et al., 2001).

The largest effects of future climatic variability or change on Northwest forests are likely to arise from changes in fire frequency and severity. Changes in other disturbances, such as wind, insects, and disease, are also possible under climatic change, although the potential character of these disturbances under climatic change is poorly understood. General warming is likely to encourage northward expansion of southern insects, while longer growing seasons are highly likely to allow more insect generations in a season. Forests that are moisture stressed are often more susceptible to attack by insects such as bark beetles and spruce budworm, although the timing and magnitude of effects varies greatly (e.g., Thomson et al., 1984; Swetnam and Lynch, 1993). Interactions between multiple disturbances (e.g., between insects and fire) will be especially important under projected climatic change.

6. Adaptive Capacity

The vulnerability (to climatic variations and change) of an ecosystem or institution is determined both by its *sensitivity* to climatic variations, and by its *adaptability* or resilience. Sections 3–5 of this paper outlined the sensitivity of some key natural resources in the Northwest; adaptability, addressed in this section, determines how strongly those resources will be affected by climatic change. A comprehensive evaluation of the adaptive capacity of the region's unmanaged resources is beyond the scope of this paper, but in this section we provide a first evaluation of the capacity of the region's *managed* natural resources to adapt to climatic variations and change. Some conclusions below are based on formal interviews, but most are subjective inferences based on communications with resource managers and decision makers. We pay most attention to water resources for two reasons: because the impacts of climate variations are better quantified than for biological resources, and because there is a clear operational link between climatic conditions and routine decisions.

For a given decision-making process concerning a natural resource that is sensitive to climatic variations, there are at least four key elements of climate awareness, four steps (possibly but not necessarily sequential) that lead to greater adaptability. As noted by IPCC (2001b), 'Experience with adaptation to climatic variability and extremes can be drawn upon to develop appropriate strategies for adapting to anticipated climatic change'.

1. *Sensitivity.* Recognize and analyze the influence that past climatic variations have played in variations of important quantities. For example, this could mean quantifying the link between El Niño events and flooding in a particular river, or between low-snow years and growth of a particular tree species.
2. *Operations.* Incorporating seasonal forecasts, either of ENSO conditions or of temperature and precipitation, into decision-making.
3. *Long-term planning.* Incorporating climate-change projections into long-range plans (like maintaining water supply or siting infrastructure), rather than relying solely on the past as a guide to the future.
4. *Policy.* Proactively changing policies and institutions to allow for greater adaptability to a changing climate.

This section describes progress on these four steps by managers of each of the major resources discussed in Sections 3–5.

6.1. FOREST RESOURCES

Recognizing sensitivity. Managers of forest resources have been reluctant even to recognize sensitivity to climatic variations. Research (e.g., Peterson and Peterson, 2001) demonstrates that year-to-year and decade-to-decade climatic variations affect tree growth and suggests that seedlings are vulnerable to a single year of poor growing conditions, possibly leading to a costly stand failure. But forest managers tend to dismiss such research as irrelevant because the long lifespan of trees (typically at least 40 years on land used for timber production) averages so many years of climate; the risk of stand failure is seen as random.

Using forecasts in operations. In our surveys, forest managers in the Northwest saw no reason to use seasonal forecasts except as background, though they are generally aware of their existence (Fluharty et al., 1998). The main reason is a lack of quantitative connection between seasonal climatic variations and quantities of interest, chiefly as they affect timber harvest operations. The greatest interest was in fire weather forecasting. There are undoubtedly untapped opportunities in the forest management sector for using seasonal forecasts.

Long-term planning. Because nearly all forests in the Northwest are under some form of human management, forest management and land-use change are likely to remain the predominant factors that shape the structure, species mix and extent of forest ecosystems. Managers of commercial forests will need to consider how long-term climatic change may affect planning and investment. In Scotland, forest managers are beginning to consider climatic change when deciding which types of trees to plant (S. Hodge, pers. communication, 2000). Managers in the PNW, by contrast, are far from doing so, partly from reluctance to believe scientific assessments that climate is changing.

6.2. SALMON

Recognizing sensitivity. There is a growing recognition within the fisheries research, management, and harvest communities that climatic variations have an important influence on the resource, but useful quantitative details are sometimes elusive. For salmon, much work has demonstrated the connections between climatic variations in the Pacific Ocean and the abundances of salmon (Beamish and Bouillon, 1993; Mantua et al., 1997; Hare et al., 1999) and of other marine taxa (Hare and Mantua, 2000). These connections are now widely recognized (see jisao.washington.edu/pdo/ for a list of academic papers and media articles). However, climatic connections are elusive for other species and even for some salmon stocks. Collecting biological data, especially at sea, is considerably more challenging than collecting streamflow data, and the sensitivity of organisms to climatic variations is often confounded by other environmental influences, like rates of predation, competition, etc.

Using forecasts in operations. Pulwarty and Redmond (1997) evaluated the use of seasonal forecasts in the management of salmon in the Columbia River basin, and found that the most direct application of seasonal forecasts was for streamflow. However, they found little or no evidence that fisheries managers were considering seasonal forecasts. Our own experience indicates that little has changed since 1997. Only a few agencies even consider climatic variability in making resource forecasts: The Alaska Department of Fish and Game uses climate indicators in assessing the uncertainty of 'productivity regimes' when making annual salmon forecasts, and the International Pacific Halibut Commission uses PDO in making forecasts of halibut abundance.

Long-term planning. Prompted by the listing of numerous Northwest salmon stocks under the Endangered Species Act, many jurisdictions have undertaken habitat conservation plans with a view to ensuring long-term recovery of salmon. Such plans could have included a consideration of climatic change, but to our knowledge none did so.

6.3. WATER RESOURCES

6.3.1. *Recognizing Sensitivity to Climate*

For many aspects of water resources, sensitivity to climatic variations is often solidly demonstrated and formally recognized in management practices. For example, reservoir rule curves, which determine how releases from a reservoir can proceed throughout the year, are based on some fairly long (usually at least 50 years) records of past streamflow. These long records offer a way to quantify and balance the risk of failing to meet competing objectives. Infrastructure (roads, bridges, buildings, etc.) is often constructed to withstand a 50- or 100-year flood, where flood frequency is derived from observations using statistical assumptions about the shape of the probability distribution. These detailed estimates of risk are possible in part because streamflow measurements are straightforward, abundant, and generally long-lived, leading to an abundantly clear connection between climate and the resource. There is a danger, however, in relying too heavily on past records if climate changes and the future statistics are unlike the past statistics.

6.3.2. *Using Seasonal Climate Forecasts in Operations*

Streamflow, and by extension water resource objectives, is a prime candidate for the application of seasonal forecasts because it is easily quantified and is quantifiably related to predictable climatic variations. However, there are profound institutional barriers to the use of forecasts (Glantz, 1982; Callahan et al., 1999), including legal or regulatory constraints and the demands of managers that forecasts meet presently unattainable criteria for accuracy (e.g., greater than 75% accuracy; Pulwarty and Redmond, 1997), spatial specificity (sub-watershed scale; Callahan et al., 1999) or lead time (1 year or more; *ibid.*). These institutional barriers are especially acute in the Columbia River Basin.

6.3.3. *Using Forecasts in the Columbia River Basin*

At present, snow-based streamflow forecasts are issued only beginning in January, and there is institutional resistance to the use of earlier, climate-based forecasts. If seasonal forecasts were used for the August–December period, additional hydropower production in expected wet years (especially cool phase ENSO – cool phase PDO) could increase revenue on the order of 4%, or $150 million, per year on average, and much more in wet years, without compromising reliability of other objectives (Hamlet et al., 2002).

Under current institutional arrangements, the benefits of seasonal forecasts would be distributed only to one use of the resource (hydropower); other interests would presumably resist such an untried system out of fear of loss. And if the forecast were used even once without clear success, i.e., if some objectives suffered or were perceived to suffer because high streamflow did not materialize, confidence in the value of seasonal climatic forecasts could take years to recover. The asymmetrical benefit distribution from seasonal streamflow forecasts could be alleviated by appropriate market mechanisms, through which senior rights holders could sell claims for available water on either spot or futures markets to junior rights holders, and the expected hydropower benefit purchased from those who own storage rights in the reservoir.

In the Columbia River Basin, an even greater difficulty, which also constrains how the region could respond to climatic change, stems from the facts that (1) there are so many entities involved in managing the river; (2) rights for water use (both for diversion and in-stream use) are partly, but incompletely, specified; and (3) there is no efficient or effective way to balance competing needs, especially in a dry year. Authority rests with many entities, including national agencies in both the U.S.A. and Canada, states, provincial, tribal, regional, and local governments, utilities, and others. Water rights are specified in different ways: diversion rights are specified through application of the Prior Appropriation doctrine (first in time, first in right; Dufford, 1995), while in-stream rights are specified in a non-integrated manner, with jurisdiction spread among several agencies and/or rights-holding groups. Finally, and most crucially, *no single entity, whether government agency or free market, determines how the pain is shared in shortages*. Consequently, there is no clear route for seasonal forecast information to enter the complex and inefficient pattern of decision-making, though in our conversations with managers in the last few years it is clear that even those who do not yet use the forecasts pay attention to them.

6.3.4. *Using Forecasts for Seattle's Water Supply*

If the Columbia River Basin represents an extreme example of complexity, rigidity, and lack of coordination, at the other extreme is Seattle Public Utilities (SPU), perhaps the best example of a public agency rapidly adopting new methods for managing a resource. SPU provides water for the City of Seattle and numerous suburbs, and it illustrated institutional flexibility and learning during a sequence of three summer droughts and potential shortages in the El Niño years of 1987, 1992 and 1998 (Gray, 1999, *et seq.*). In response to the 1987 drought, SPU developed a plan to manage anticipated shortages with four progressive levels of response:

1. advising the public of potential shortages and monitoring use
2. requesting voluntary use reductions
3. prohibiting inessential, high-consumption uses such as watering lawns and washing cars
4. rationing.

Another water supply shortage came in 1992, following a winter with low snow-pack but during which SPU had spilled water from its reservoirs to comply with flood-control rules. Reservoirs were low by the spring, and SPU invoked mandatory restrictions during the hot dry summer that followed. The resultant low demand increased the residence time in the distribution system and caused water quality in the distribution system to decline. Low reservoir levels also caused a decline in the quality of source water, prompting a decision to build a costly ozone-purification plant.

Its regrettable spilling of early 1992 alerted SPU to the risks inherent in following rigid reservoir rule curves, especially in El Niño years. Since then, SPU has used a model that includes both ENSO and PDO to generate probabilistic projections of supply and demand six to twelve months in advance. Using this model during the strong El Niño of 1997–1998, SPU undertook conservation measures early in the year, including both weekly public announcements of supply conditions and allowing higher than normal winter reservoir fill. When 1998 brought a small snowmelt and a hot dry summer, these measures allowed the drought to pass with the public experiencing no shortage. In 2001, the Northwest experienced the worst drought since 1977, with precipitation in Seattle's water supply area only about 60% of normal, but SPU handled the drought well; stage 2 (voluntary reductions) were effective, allowing the city to refill its reservoirs in May and avoid moving to stage 3 (water use restrictions) (SPU, 2001).

6.3.5. *Planning for Climatic Change*

If it has been an uphill battle persuading resource managers that seasonal forecasts can add valuable knowledge to the decision process, it has been a Sisyphean task to effect meaningful adaptations to climatic change, but we will shortly report a number of hopeful signs. Adaptation to climatic change comes in two main avenues (the last two entries in the list at the beginning of Section 6): incorporating the notion of climatic change into long-range plans and proactively changing institutions to improve adaptability. The former is generally easier than the latter, perhaps because entrenched interests resist institutional change and because it may not be clear what changes would be needed. Most of the discussion that follows focuses on long-range planning rather than on institutional change.

There are three main options for adapting to climatic change with respect to water resources (e.g., IPCC, 1995; Snover et al., 1998):

- Increase supply
- Decrease demand (e.g., through pricing)
- Increase institutional flexibility.

IPCC (2001b) notes that 'supply-side approaches … are more widely used than demand-side approaches (which alter the exposure to stress)'. The value of reducing demand was underscored by the experience of Seattle Public Utilities, whose successful management of demand (Section 6.3.4) has reduced vulnerability to drought.

Increasing supply in the Northwest could take several forms, including new storage through dams or groundwater recharge, using non-potable supplies for some uses (like watering lawns in parks, golf courses, and cemeteries), and developing new groundwater sources. New dams are unlikely, owing to high environmental costs and scarcity of feasible sites. Groundwater recharge is being practiced on a limited scale in the Snake River plain and could be expanded. These various strategies are being pursued as a means to increase supply because of current shortages, not shortages anticipated as a result of climatic change, although (owing to efforts by the UW Climate Impacts Group) climatic change was given as one reason for increasing storage in the state of Washington (Water Storage Task Force, 2001). A few officials acknowledge the need to include climatic change in long-range plans, and are taking steps to do so, but generally it is not widely recognized as a factor to consider in future supply plans.

Demand-side management is often politically less palatable than increasing supply. Agricultural use of water accounts for the vast majority of consumptive use in the Columbia River Basin, so reducing demand for water in the Basin would affect irrigated agriculture. Water usage is heavily subsidized and in general there is no 'price' for water used; there is consequently no means for optimizing the allocation of water among different uses. For example, high-value crops representing multi-year investments, like wine grapes, are not necessarily more likely to receive water during shortages than low-value annual crops like alfalfa. Improvements in efficiency have already been undertaken, but in some places have allowed more total consumption, thereby returning less water to the rivers (Gray, 1999). In southern Idaho (B. Ondrechen and G. Newton, IDWR, personal communication, 2001) gains in efficiency following the 1977 drought have actually reduced withdrawals over the last two decades because irrigated acreage has not increased. Western water law's 'use it or lose it' feature is a strong disincentive to conservation, because a temporary reduction in use can lead to permanent relinquishment (G. Schuler, pers. communication, 2002). A continuing shift from annual crops to more lucrative perennials, such as tree fruit, grapes and hops, has further exacerbated vulnerability: some perennials consume more water, and perennials generally reduce farmers' flexibility to alter their planting in dry years, and put many years' investment at risk from a single drought, further increasing incentives to pump groundwater (Gray, 1999; G. Schuler, pers. communication, 2002).

The third category of adapting to climatic change, increasing institutional flexibility, is perhaps the most difficult, especially in the Columbia basin. As Miles et al. (2000) note, the Columbia has high adaptability to high flows because a single entity (the Army Corps of Engineers) has authority to determine how reservoirs are managed, but adaptability to low flows is poor because of institutional fragmentation. Times of scarcity bring conflicts among the dozens of entities with disparate interests and with power over various overlapping geographic portions of the basin. In addition to these jurisdictional layers, there are institutional layers created by decades of lawmaking aimed at solving a wide range of disparate problems. Chief among them are the Columbia River Treaty with Canada (1964), which improved binational cooperation in hydropower and flood control operations, and the Northwest Power Planning and Conservation Act (1980), which theoretically established salmon protection as a priority equal to hydropower in law (though as Miles et al. (2000) showed, the *de facto* operating priorities still place fish protection well behind hydropower). Water management in the Columbia Basin is, as a result of these jurisdictional and institutional layers, extremely difficult to change, and Miles et al. (2000) concluded that 'The inflexibility of the water management system will significantly impact the ability of the PNW to cope with these future changes'.

Stimulus for institutional change is likely to come from droughts, and experience in dealing with droughts in the Yakima Valley is illuminating. A microcosm of the Columbia River Basin and its water issues, the Yakima Valley in south central Washington (see Figure 1) is one of the driest places in the United States (as little as 18 cm of annual precipitation, nearly all in winter) and yet contains some of its most fertile farmland, 80% of it irrigated. Yakima Valley agriculture has reacted to rhythms of shortage and plenty, which in turn follow the PDO cycle (Gray, 1999). Water shortages have occurred eight times since 1945, all but once in warm-PDO years, and typically lead first to emergency permits for temporary pumping from wells and then to new policies. During times of plenty, like the last cool phase of the PDO (1945–1976), expectations of continued abundance of water led to expansion of agriculture. Some initiatives to improve management of Yakima Valley's water are underway, but the valley still lacks a coherent basin-wide drought strategy (J. Milton, pers. communication, 2001). Moreover, if agricultural expansion continues, whether pushed by market forces or pulled by several years with abundant water supply, such expansion would further increase the region's vulnerability to future recurrence of dry conditions (Gray, 1999).

6.4. WAYS FORWARD

There are wide variations in the adaptive capacity of institutions that manage natural resources in the PNW. Improving adaptive capacity means becoming more resilient to climatic variations (for which the past is an essential guide) and proactively reducing vulnerability to climatic change (for which the past may be less useful, or even may prove misleading). Most natural resource managers in the region appear to be interested in the notion of a changing climate, but generally have not begun seriously to consider what they would have to do differently now to reduce vulnerability to a changing climate. In some cases (e.g., municipal water utilities), institutional hurdles for considering climatic change are relatively low; in others (Columbia Basin water resources, forest management) the institutional hurdles are high. The best ways forward are likely to be those for which the benefits are accrued to society as a whole via returns to individuals: motivating individual actions that produce both personal gain and collective good.

Several possible strategies can be outlined for adapting forests to climatic change. Maintaining biodiversity – especially by planting trees whose genotypes have a broad range of environmental tolerance – spreads risk and reduces vulnerability to environmental stresses like climatic variations and extremes. For individual trees, the greatest vulnerability occurs at the seedling phase of life and (geographically) at the margins of their ranges; recognizing the influence of a changing climate on these vulnerable parts of the forest ecosystems would be a prudent step. Another approach, particularly for unmanaged forests, would expand or adjust the region's protected areas to incorporate greater geomorphic or landscape diversity, thereby facilitating distributional or range-shifts in terrestrial communities and enhancing ecosystem resilience to change. Other adaptive strategies (Mote et al., 1999b) include managing forest density for reduced susceptibility to drought stress, using prescribed fire to reduce vulnerability to large fires, and monitoring trends in forest conditions and climate.

Managing salmon for a changing climate could, in theory, be based on the same broad strategy as for forests: biodiversity. Salmon have evolved a wide range of life history strategies (the timing of their transitions from one life phase to the next) in order to deal with environmental uncertainty, and preserving that diversity offers the best hope for Northwest salmon in a warming climate. Preserving diversity means conservation and restoration of freshwater and estuarine habitat, ensuring that fishing practices are sustainable and do not excessively impact any one stock, and managing hatchery programs to minimize harm done to wild stocks (Mote et al., 1999b). Some habitat restoration efforts are underway in the Northwest, prodded by the listing of several salmon stocks and other species under the Endangered Species Act, but the notion and implications of a changing climate have yet to influence such efforts.

Adaptation of water resources may benefit from recent experience. With regional precipitation about 65% of normal in water year 2001 (10/2000–9/2001), the 2001 drought caused widespread problems, perhaps nowhere more so than in the Klamath River basin in southern Oregon, where the U.S. Bureau of Reclamation shut off irrigation water to some farmers in order to meet stream flows and reservoir levels required under the Endangered Species Act. Oregon Governor John Kitzhaber, M.D., proposed a lasting remedy for the Klamath problem ('a permanent downsizing' of demand) and warned that similar problems face the Columbia Basin as well, and called for a 'new regional governance model' in which authority would be transferred from the Federal government and its various agencies to a regional authority that would be a better steward of the river (see Slaughter et al., 2002). Such an approach would, in our view, simply add another layer of jurisdiction and complexity, and would be difficult to implement because it would be opposed by anyone who benefits from the current system.

A more effective policy solution might begin by better specifying water rights, in order to provide the required basis for a more complete market solution (Slaughter et al., 2002). Such a solution might involve a once and forever purchase of water rights for instream uses like hydropower or fish protection, or the creation of a more robust market, complete with futures trading and flow forecasts, wherein junior rights holders and others could acquire water as needed.

There is evidence that water transfer institutions, or markets, are emerging in Idaho. An early step was taken in 1979 with the creation of the Idaho Water Bank, in which water can be temporarily transferred between uses as a beneficial use. In 2001 the Idaho Public Utilities Commission approved irrigation electricity buybacks for two Idaho utilities, through which water was left in the stream because irrigators did not pump for the year. In the same year, the Idaho Department of Water Resources came close to curtailing sub-surface pumping in two districts, after which the Committee of Nine, a quasi-governmental entity that has allocated natural flow and stored water in southern Idaho since 1926, authorized sale of water at up to $50 per acre-foot. In 2002, there were negotiations for at least one purchase of water rights (for instream use) from a large irrigation project, and for several years industrial users have purchased the water rights for unwatered 'corners' left by irrigation pivots, moving the use from irrigation to industrial.

Ultimately, the process of enhancing adaptability through monumental institutional changes may only be undertaken after severe basin-wide crises like the Klamath problem, though the UW Climate Impacts Group is working to promote a more pro-active approach. Outside the Columbia Basin, institutional change is more likely, owing to a combination of more plentiful supply in relation to current demand, a simpler institutional picture, and greater cooperation among uses. The state of Washington is pursuing legal changes that would allow municipal water suppliers more flexibility in exchanging water (T. Fitzsimmons, pers. communication, 2001). Seattle Public Utilities presently projects that new conservation measures will keep demand at or below present levels until at least 2010, and along with a planned system expansion will maintain adequate supply until at least 2030 (A. Chinn, Seattle Public Utilities, personal communication, 2000). Over this period, climatic change is likely to have significant effects on both supply and demand, and SPU, in partnership with CIG, is beginning to quantify the impacts of climatic change on SPU's water resources.

Improving adaptive capacity will require a parallel strategy of (1) incorporating climatic change into long-range plans and (2) in some cases modifying institutional arrangements. In both cases, the scientific findings of the Climate Impacts Group and other researchers can play a crucial role. Early progress in some institutions (e.g., Seattle Public Utilities) may inspire confidence in adaptive efforts elsewhere. Crises like the 2001 drought may, however, be the main driver for institutional change.

7. Conclusions

Our analyses have characterized the sensitivity of three key resources in the Pacific Northwest – freshwater, salmon, and forests – to both the observed patterns of inter-annual and decadal climatic variability over the 20th century, and the climatic trends projected by eight climate models under anthropogenic greenhouse warming for the first half of the 21st century.

The studies of the effects of 20th-century climatic variability show substantial climate sensitivity in all three resources studied, although the magnitude and extent of the effects, and the degree of understanding of causal mechanisms, differ among the three. The case for freshwater resources is the clearest: the warm phases of the PDO and ENSO each reduce annual flow in the Columbia by about 10% relative to the long-term mean (with larger changes in the peak June flow), while the cool phases increase flows by about the same amount. These changes are associated with clear changes in regional risks of droughts (in warm-phase years) and floods (in cool-phase years). For salmon, the historical record of climate sensitivity is also clear – the warm phase of PDO reduces the size of most salmon stocks in the Pacific Northwest (while increasing them in Alaska and northern British Columbia) – but the mechanisms causing these changes are not yet understood. For forests, the processes shaping climatic influence are somewhat better understood – principally the diverse effects of reduced snowpack in warm-phase years on trees growing at different elevations and under different moisture regimes – but the observed effects are more limited in extent. The PDO has clear effects on growth of forests near their upper and lower-elevation limits (opposite in sign), and a suggestive effect on fire, but no effect is evident on established stands at medium elevations. Taken together, these results indicate both greater climate sensitivity of key regional resources than previously recognized, and greater predictability of these effects because of their association with known patterns of climatic variability.

These empirical studies of 20th-century climatic sensitivity provide a foundation and a comparative reference for our model-based projections of regional climate impacts over the 21st century. Although there is substantial variation between the projections of different climate models, all models show regional trends toward warmer temperatures, with smaller and more variable changes in precipitation, so that by the 2040s, all models project regional temperatures well above the observed range of 20th-century variability. As in the 20th century analyses, the projected effects on the three resources studied differ in magnitude, spatial extent, and confidence of understanding. For water resources, all climate scenarios lead (with high confidence) to the large-scale loss of snowpack at moderate elevations by mid-century, bringing large reductions in summer flow in all streams and rivers that depend on snowmelt. For salmon, there are qualitative indications that regional climatic change will impose additional stresses, but the effect cannot yet be quantified or indeed even ranked relative to all the other stresses salmon are suffering. For forests, the first-order effects of reduced snowpack will enhance establishment and growth at high elevations and increase drought stress at lower elevations, but the effects will depend strongly on the site and moisture conditions of specific stands, and are subject to two important uncertainties: the magnitude and consequences of CO_2-induced increases in water-use efficiency, and the capacity for increased seasonal soil-moisture storage, which could allow increased winter rains to offset the increased drought stress from warmer summers.

In aggregate, our preliminary analyses suggest that regional climatic impacts in the Pacific Northwest over the next 50 years are likely to be seriously challenging and uncomfortable – not catastrophic – and to require significant adjustment and adaptation in the sectors most affected. These analyses represent significant advances in understanding, but are also subject to several large-scale uncertainties, some obvious, some less so. The results clearly depend upon the uncertainty in the climate-model projections used to drive them, although our use of eight different climate models provides some basis for confidence – particularly in those results, such as decreased summer stream flows, that are consistent across all models. Results also depend, although less strongly, on the assumed growth rate of worldwide greenhouse-gas emissions. While we have not considered this uncertainty (all the climate models considered here were driven by just one emission scenario), recent results suggest that alternative emission pathways will have only small climatic effects over the 20 to 50-year time horizon that we consider here (e.g., Stott and Kettleborough, 2002). Later in the 21st century the effect of alternative emission scenarios becomes much stronger, so longer-term impact analyses must consider this uncertainty.

Even over the 20 to 50-year horizon we consider, many other socio-economic and environmental trends will evolve jointly with climatic change. Our studies have made significant advances in assessing the effects of linked climatic and socio-economic trends, e.g., in jointly projecting climate-driven changes in freshwater supply with demand increases arising from climatic change and from regional growth. Still, such attempts to characterize impacts and vulnerabilities by jointly projecting climatic changes and other salient trends are in their infancy, and require much more effort.

More work is also needed to characterize existing capacity to adapt to climatic changes and to identify ways to increase it. Our historical studies allow some observation of the extent and character of adaptive response to climatic fluctuations, or in some cases maladaptive response. Social and economic measures taken to respond to or anticipate future climatic changes will be major determinants of ultimate impacts, but little is known at present about the value and effects of specific potential adaptation measures or the factors shaping broader social capacity for adaptation. Indeed, since climatic change is unlikely to become the highest priority on policy agendas, one must also consider the possibility that policy decisions or socio-economic trends may lead to increased, rather than decreased, vulnerability to climate-related disruptions.

In sum, the priority directions for further characterization of regional climate impacts and vulnerabilities in the Pacific Northwest are as follows: (a) examination of additional domains of impact (e.g., agriculture, human health) and, crucially, potential interactions between impact domains; (b) interactions of climatic with other regional trends (both environmental and socio-economic), to prioritize risks, examine interactions, and identify potential opportunities for adaptation and key vulnerabilities; (c) refining the characterization of uncertainties, both in regional climatic trends and in the climatic responses of resources, ecosystems, and socio-economic systems, over various time horizons as relevant to key long-term decisions; (d) extending the analyses beyond 50 years, to characterize the response of regionally important resources and systems to the larger climatic changes projected for that period and to examine the effects of alternative pathways of future emissions.

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Appendix: Data Sources and Modeling Details

Climate data. For studying interannual variations, we use climate division data (http://www.cdc.noaa.gov/USclimate/USclimdivs.html), which are available from January 1895 to the month just completed (updated monthly). We use data from 1899 to 1999. For calculating long-term trends, we use historical climate network (HCN) data (Karl et al., 1990), which provide quality-controlled climate data at individual stations as far back as 1878. For calculating region-wide trends, these station data are first aggregated by climate division and then area-averaged.

Streamflow data. The Columbia River flow has been changed substantially over the years as dams have been constructed, but the effects of these changes can be estimated by considering diversions, storage, and increased evaporation, and then removed. The results match closely with those simulated independently by our hydrology model (Hamlet and Lettenmaier, 1999). In this paper we use only these 'naturalized' flows.

Population data. In connection with the U.S. National Assessment of the Potential Consequences of Climate Variability and Change (National Assessment Synthesis Team, 2001), a set of population projections are available at county-by-county spatial resolution and at 10-year intervals to 2050 (Terleckyj, 1999a,b). The data were analyzed for the PNW in Mote et al. (1999b) by Benjamin Noble.

Control runs of climate models. There is a subtle difficulty in comparing the projected warming rates of different models. Each of the modeling teams responsible for these climate models also performed a 'control' integration using a fixed concentration of CO_2 chosen by the modeling team.⋆ Because this CO_2 concentration affects the radiative forcing, we would expect slightly higher global average temperatures for higher CO_2 values, and there is some possibility that *regional* temperatures would also be higher for higher CO_2 values. The HadCM3 run used a preindustrial concentration (290 ppmv) for the control run but the other models used values between 315 and 355 ppmv (corresponding to 1966 and 1993 respectively; see cdiac.esd.ornl.gov).

⋆ Despite the importance of the CO_2 concentration, many of the papers did not report the value used in the control runs. Personal communications filled the gaps.

To improve comparability, we have used PNW temperature and global CO_2 to provide a reference point for the various control runs. We derived a CO_2-fitted PNW temperature history T_{CO_2} by regressing the annual regional mean temperature (derived from HCN data) on $\ln(CO_2)$, reflecting the expected relationship between temperature and CO_2. (Note that this is the simplest of several expressions for the dependence of radiative forcing (IPCC, 2001a, p. 358), and lumps together the forcing by all greenhouse gases and other anthropogenic influences like sulfate aerosols.) This CO_2-fitted temperature curve is then used in Figure 4c to report temperature changes from the control run. For example, HadCM2 used a CO_2 concentration of 323 ppmv, which prevailed in 1968, so the changes from control to 2020s and 2040s are indicated with respect to the CO_2-fitted PNW temperature for 1968.

Finally, for reporting in Table I, the changes for each model are adjusted so that they refer to observed 1990's temperatures. This procedure is summarized in the following equation:

$$\langle \delta \mathrm{T}_{2020\mathrm{s}} \rangle = \langle \mathrm{T}^{\mathrm{m}}_{2020\mathrm{s}} \rangle - \langle \mathrm{T}^{\mathrm{m}}_{\mathrm{control}} \rangle + \langle \mathrm{T}_{\mathrm{CO}_2}(\mathrm{yr}) \rangle - \langle \mathrm{T}^{\circ}_{1990\mathrm{s}} \rangle ,$$

where $\langle \mathrm{T} \rangle$ indicates the regional average of T, T^{m} is the modeled temperature, T° is the observed temperature, T_{CO_2} is the CO_2-fitted temperature, and yr is the year when observed CO_2 values corresponded with the value used in the model's control integration. This adjustment procedure ignores ocean lags, but is an improvement over treating all the control runs the same.

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