CHAPTER 9

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE PACIFIC NORTHWEST

Edward A. Parson[1,2], with contributions from members of the Pacific Northwest Assessment Team: Philip W. Mote[3], Alan Hamlet[4], Nathan Mantua[5], Amy Snover[6], William Keeton[7], Ed Miles[8], Douglas Canning[9], Kristyn Gray Ideker[10]

Contents of this Chapter

---

[1] John F. Kennedy School of Government, Harvard University, [2] Coordinating author for the National Assessment Synthesis Team, [3] University of Washington (UW), Chair, Pacific Northwest Regional Assessment Team, [4] Dept of Civil and Environmental Engineering, UW, [5] Climate Impacts Group, UW, [6] Climate Impacts Group, UW, [7] College of Forest Resources, UW, [8] Climate Impacts Group, UW, [9] Washington State Dept of Ecology, Olympia, [10] Ross and Associates (work completed while at UW)

CHAPTER SUMMARY

Regional Context

The Northwest, which includes the states of Washington, Oregon, and Idaho, has a great diversity of resources and ecosystems, including spectacular forests containing some of the world's largest trees; abrupt topography that generates sharp changes in climate and ecosystems over short distances; mountain and marine environments in close proximity, making for strong reciprocal influences between terrestrial and aquatic environments; and nearly all the volcanoes and glaciers in the contiguous US. The region has seen several decades of rapid population and economic growth, with population nearly doubling since 1970, a growth rate almost twice the national average. The same environmental attractions that draw people and investment to the region are increasingly stressed by the region's rapid development. The consequences include loss of old-growth forests, wetlands, and native grass and steppe communities, increasing urban air pollution, extreme reduction of salmon runs, and increasing numbers of threatened and endangered species. Climate change and its impacts will interact with these existing stresses in the region.

Climate of the Past Century

- Over the 20th century, annual-average temperature in the Northwest rose 1 to 3°F (0.6 to 1.7°C) over most of the region, with nearly equal warming in summer and winter.
- Annual precipitation increased nearly everywhere in the region, by 11% on average, with the largest relative increases about 50% in northeastern Washington and southwestern Montana.
- Year-to-year variations in the region's climate show a clear correlation with two large-scale patterns of climate variation over the Pacific, the El Niño/Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO). The region-wide pattern associated with these phenomena is that warm years tend to be relatively dry with low streamflow and light snowpack, while cool ones tend to be relatively wet with high streamflow and heavy snowpack. This has clear effects on important regional resources: warmer drier years tend to have summer water shortages, less abundant salmon, and increased risk of forest fires.

Climate of the Coming Century

- Regional warming is projected to continue at an increased rate in the 21st century, in both summer and winter. Average warming over the region is projected to reach about 3°F (1.7°C) by the 2020s and 5°F (2.8°C) by the 2050s.
- Annual precipitation changes projected through 2050 over the region range from a small decrease (-7% or 2") to a slightly larger increase (+13% or 4").
- Projected precipitation increases are concentrated in winter, with decreases or smaller increases in summer. Because of this seasonal pattern, even the projections that show increases in annual precipitation show decreases in water availability.

Key Findings

- Projected warmer wetter winters are highly likely to increase flooding risk in rainfed rivers, while projected year-round warming and drier summers are highly likely to increase risk of summer shortages in both rainfed and snowfed rivers, because of smaller snowpack and earlier melt.
- Salmon are likely to be harmed by increased winter flooding, reduced summer and fall flows, and rising stream and estuary temperatures. It is also possible that earlier snowmelt and peak streamflow will deliver juveniles to the ocean before there is enough food for them. Climate change is consequently likely to hamper efforts to restore depleted stocks, and to stress presently healthy stocks.
- The coniferous forests that dominate much of the Northwest landscape are sensitive to summer moisture stress. Their extent, species mix, and productivity are likely to change under projected 21st century climate change, but the specifics of these changes are not yet known.
- Sea-level rise will likely require substantial investment to avoid coastal inundation, especially in low-lying communities of southern Puget Sound where the coast is subsiding. Projected heavier winter rainfall is likely to increase soil saturation, landsliding, and winter flooding.
- El Niño events increase erosion both by raising sea level for several months and by changing the direction of winds and waves from westerly to southwesterly. Climate change is projected to bring similar changes and associated impacts, including severe storm surge and coastal erosion.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE PACIFIC NORTHWEST

PHYSICAL SETTING AND UNIQUE ATTRIBUTES

The Pacific Northwest region includes the states of Washington,Oregon,and Idaho,and for assessing impacts in the Columbia River basin,some areas in adjoining states and the Canadian province of British Columbia. The region has a great diversity of resources and ecosystems,including spectacular forests containing some of the world's largest trees; abrupt topography that generates sharp changes in climate and ecosystems over short distances;mountain and marine environments in close proximity, making for strong reciprocal influences between terrestrial and aquatic environments;and nearly all the volcanoes and glaciers in the contiguous US.

The region is divided climatically, ecologically, economically, and culturally by the Cascade Mountains. The low-lying areas west of the Cascades hold three quarters of the region's population,concentrated in the metropolitan areas of Tacoma-Seattle-Everett along the Puget Sound coast,and Portland in the Willamette Valley. Here,once-dominant forestry, fishing and agriculture have been overtaken by aerospace,computer software and hardware,trade and services,although the relatively declining resource sectors remain economically and culturally important. The Northwest still provides about a quarter of the nation's softwood lumber and plywood (Haynes et al.,1995,tables 18 and 27). Agriculture is now much more important in the east of the region. Thanks in part to massive water-management and irrigation projects,the fertile lowlands of eastern Washington are the "Fruit Bowl"of the nation,producing 60% of the nation's apples and large fractions of its other tree fruit,while Idaho produces about a quarter of the nation's potatoes (USDA, 2000).

Figure 1: The Puget Sound area has experienced rapid growth over the past two decades. Source: P. Mote, University of Washington

SOCIOECONOMIC CONTEXT

The region has seen several decades of rapid population and economic growth. Population has nearly doubled since 1970,a growth rate almost twice the national average. Growth has been strongly concentrated in the major western metropolitan areas and in the smaller but fast-growing inland cities of Boise and Spokane (Jackson and Kimmerling,1993). Federal lands comprise roughly half the region's land area.[1] The region's environment presents a great variety of outdoor recreational opportunities, and its moderate climate and quality of life contribute to its continuing attraction to so many newcomers. The region is projected to continue growing faster than the national average,its population increasing from the present 10.5 million to 19 million by 2050 (with a range of 14.5 million to 23 million) (Terleckyj 1999a,1999b;US Census Bureau, 2000). Both recent and projected growth rates are similar east and west of the Cascades (very slightly higher on the west),so the west side is projected to continue to contain nearly three quarters of the region's population.

The same environmental attractions that draw people and investment to the region are increasingly stressed by the region's rapid development. The predominant current stresses arise from direct

---

[1] Federal lands are 30% of Washington,48% of Oregon,and 64% of Idaho,or 48% of the region overall,with an additional 5% state-owned. (Jackson and Kimmerling 1993,p.32).

human interventions in the landscape, through such activities as dam building, forestry (including replacement of natural forests by 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, increasing urban air pollution, extreme reduction of salmon runs, and increasing numbers of threatened and endangered species.

ECOLOGICAL CONTEXT

The Northwest has a great diversity of landscapes and ecosystems, reflecting the region's varied climate and topography. Dense, tall moist coniferous forests cover about 80% of western Washington and Oregon, with Douglas fir, western red cedar and western hemlock at most low-elevation locations, western hemlock and Pacific silver fir at middle elevations, and mountain hemlock at high elevations (Franklin and Dyrness, 1973). A century of commercial logging has cut nearly all this forest at some time, greatly altering its species and age distribution. Only 10 to 20% of the original extent remains as old-growth forest (Marcot et al., 1991; Kellogg, 1992). The west also includes oak forests and grasslands in low-lying river valleys, coastal salt marshes and freshwater wetlands, and in the Klamath Mountains of southern Oregon, a mixed forest of drought-resistant conifers and hardwoods (Mac et al., 1998, p.646). East of the Cascade crest, the drier climate and more frequent fires generate an open, park-like forest of ponderosa pine and Douglas fir, with sub-alpine fir, Engelmann spruce and patches of alpine larch at higher elevations and whitebark pine especially prominent near the upper tree line. In the Rocky Mountains and the east slope of the Cascades, forest gives way at high elevations to alpine meadows, and at lower elevations to juniper woodlands, sagebrush steppe, and grasslands, as well as high desert and lava fields in Idaho.

As on the west side of the Cascades, human influence has greatly altered east-side ecosystems. Fire suppression, grazing, and selective cutting have transformed all but a few percent of the original ponderosa pine forest into overstocked mixed-species forests that are highly susceptible to fire, insects, and disease (Henjum et al., 1994). More than 99% of the prairie grasslands near the meeting point of Idaho, Oregon, and Washington have been converted to crops, mostly wheat, while about 90% of the sagebrush steppe on the Snake River plain in Idaho has been converted to agriculture (Mac et al., 1998, p.649; Noss et al., 1995). Grazing has transformed nearly all of the remaining grassland and sagebrush steppe, leading to large-scale replacement of native perennials with invasive annuals such as Cheatgrass, Medusahead and Yellow Starthistle, and to expansion of Juniper woodlands into former rangeland (Miller and Rose, 1995; Miller and Wigand, 1994; West and Hassan, 1985).

Figure 2: Old-Growth Douglas Fir Forest in the Cascades. Source: T.B. Thomas, US Forest Service

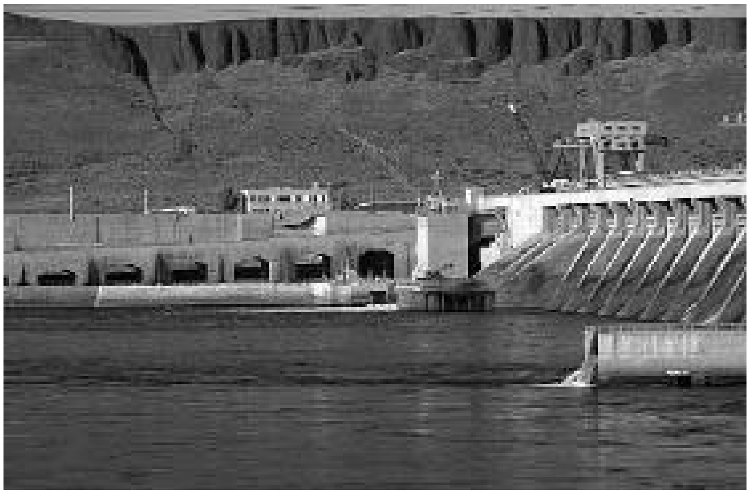


Figure 3: The Columbia is one of the most intensively developed river systems in the world. Source: ©P. Grabhorn

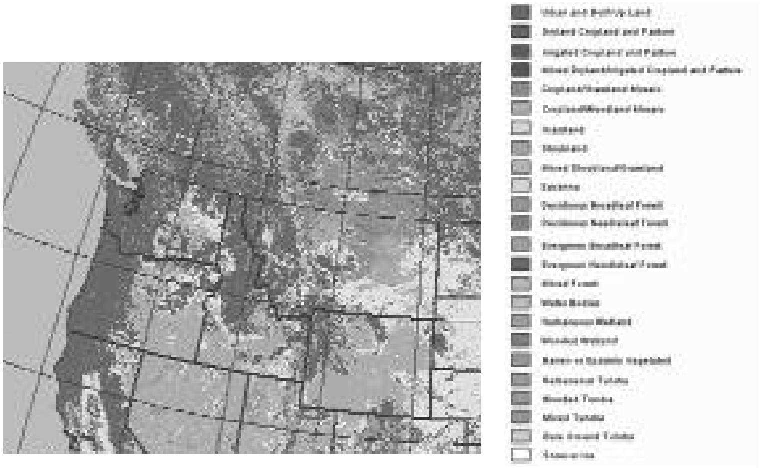


Figure 4: Major ecological regions of the Pacific Northwest
Source: United States National Atlas – See Color Figure Appendix

An additional stress on inland forests is the devastation of whitebark pine *(Pinus albicaulis)*, a dominant species near the upper tree-line in the Rockies and Cascades, by the introduced fungus,white pine blister rust. Throughout the species' range in northern Idaho more than half of the trees are dead, while infection rates of living trees are above 50% throughout Washington and Idaho,and above 20% in Oregon (Keane and Arno,1993; Kendall,1995).

The region is high in biodiversity across major taxa. In the wet west-side forests,more than 150 species of terrestrial snails and slugs have been identified, and 527 species of fungi,of which 234 are rare and occur nowhere else (FEMAT, 1993). It is estimated that these forests may support 50,000 to 70,000 species of arthropods,although only preliminary surveys of arthropods have been conducted. A survey of one experimental forest in the Oregon Cascades found more than 3,400 (Parsons et al., 1991). Oregon contains between 3,000 and 4,000 identified species of vascular plants,Idaho and Washington between 2,400 and 3,000,putting Oregon in the top six states for plant diversity and Washington and Idaho in the top 15. Of these plant species, about 8-12 are rare in Oregon,5-8 in Washington and Idaho.[2] The 33 species of amphibians in the region include 17 that are endemic,but only one candidate for federal listing,the Oregon spotted frog (Bury, 1994). Although 67 populations of fish in the region are on either federal or state sensitive species lists, much more is known about salmon and trout,the most highly valued species in the region,than about other species. Of 58 distinct salmonid stocks in the region,26 are now listed as endangered or threatened under the Endangered Species Act (ESA),including the Puget Sound Chinook,the first ESA listing to affect a major metropolitan area (NMFS,2000). Of roughly 450 species of birds identified in five sub-regions of the Northwest by the Breeding Bird Survey, from 10 to 35 species per sub-region show decreased numbers since the 1960s,while 3 to 25 show increases,with the largest net decreases in the coastal forests of southern Oregon (Carter and Barker, 1993). Among mammals,seven carnivores — the Grizzly Bear, Gray Wolf, Lynx, Wolverine, Fisher, Marten,and Kit Fox — have small and threatened regional populations, principally due to disturbance,loss of forest habitat, and the secondary effects of logging road construction (Weaver et al.,1996).

CLIMATE VARIABILITY AND CHANGE

West of the Cascades the climate of the Northwest is maritime,with abundant winter rains,dry summers,and mild temperatures year-round — usually above freezing in winter, so snow seldom stays on the ground more than a few days. Most places west of the Cascades receive more than 30 inches (75 cm) of precipitation annually, while some westward mountain slopes of the Olympics and Cascades receive more than 200 inches (500 cm). Although a mild maritime climate has prevailed in the region for several centuries,thousand-year records show substantial fluctuations. For example,from about 4,000 to 8,000 years ago in the Puget Sound area, dominance of dry vegetation types such as California chaparral suggests the region's climate was much warmer and drier, resembling the present climate of California's northern Central Valley (Detling,1953,1968).

East of the Cascade crest,the climate shifts sharply from abundant rainfall to abundant sunshine,with annual precipitation generally less than 20 inches (50 cm),as little as 7 inches (20 cm) in some places. These precipitation differences are most pronounced in winter:summer precipitation in the west is only slightly higher than in the east,while winter precipitation is four to five times higher. Figures 5 and 6 illustrate the large differences in annual and seasonal precipitation across the region. Even the inland mountain ranges receive much less precipitation than the western Cascades or Olympics. Though average temperatures are similar east and west,the east has larger daily and annual ranges,with hotter summers and colder winters.

---

[2] "Rare" means an international endangerment rank of G1 to G3 (Morse et al.,1995).

Observed Climate Trends

Over the 20th century, the Northwest has grown warmer and wetter. Annual-average temperature rose 1 to 3°F (0.6 to 1.7°C) over most of the region, with nearly equal warming in summer and winter. Annual precipitation also increased nearly everywhere in the region, by 11% on average, with the largest relative increases about 50% in northeastern Washington and southwestern Montana.[3]

In addition to this trend toward a warmer, wetter climate, the Northwest's climate also shows significant recurrent patterns of multi-year variability. These year-to-year variations tend to be consistent over the entire region, and are evident in both winter and summer. The predominant pattern is that warm years tend to be relatively dry with low streamflow and light snowpack, while cool ones tend to be relatively wet with high streamflow and heavy snowpack. Although the differences in temperature and precipitation are relatively small (differences in monthly-average temperature of up to 2 to 4ºF or 1.1 to 2.2ºC in winter), they have clearly discernible effects on important regional resources. Warmer drier years tend to have summer water shortages, less abundant salmon, and increased risk of forest fires (dell'Arciprete et al., 1996; Mantua et al., 1997; Hulme et al., 1999).

These year-to-year variations in the region's climate show a clear correlation with two large-scale patterns of climate variation over the Pacific, one more and one less well known. The El Niño/ Southern Oscillation (ENSO) is an irregular oscillation with a period of 2 to 7 years, which is widely known and intensively studied. ENSO's positive El Niño phase warms sea-surface temperature in the equatorial Pacific and cools it in the central North Pacific, deepening the winter low-pressure system off the Aleutians and bringing substantial changes in mid-latitude atmospheric circulation (Trenberth, 1997). A more recently identified pattern of longer-term variability is the Pacific Decadal Oscillation (PDO), defined in terms of changes in Pacific sea-surface temperature north of 20 degrees latitude. Like the warm El Niño phase of ENSO, the warm or positive phase of PDO warms the Pacific near the equator and cools it at northern mid-latitudes. But unlike ENSO, PDO's effects are stronger in the central and northern Pacific than near the equator, and its irregular period is several decades, tending 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 the first sea-surface temperature records in 1900 (and possibly before) until 1925, then in warm or positive phase until 1945, cool phase again until 1977, and warm phase until the 1990s (Miller et al., 1994; 1998). Evidence is beginning to mount that another change to the

Average Annual Precipitation, Pacific Northwest, 1961-1990

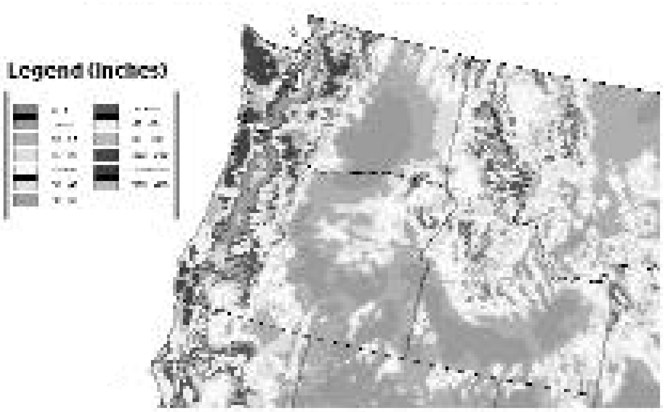


Figure 5: The Cascade mountains divide the wetter west from the drier east. Source: Mapping by C. Daly, graphic by G. Taylor and J. Aiken, copyright © 2000, Oregon State University. – See Color Figure Appendix

Average Monthly Precipitation in the Pacific Northwest

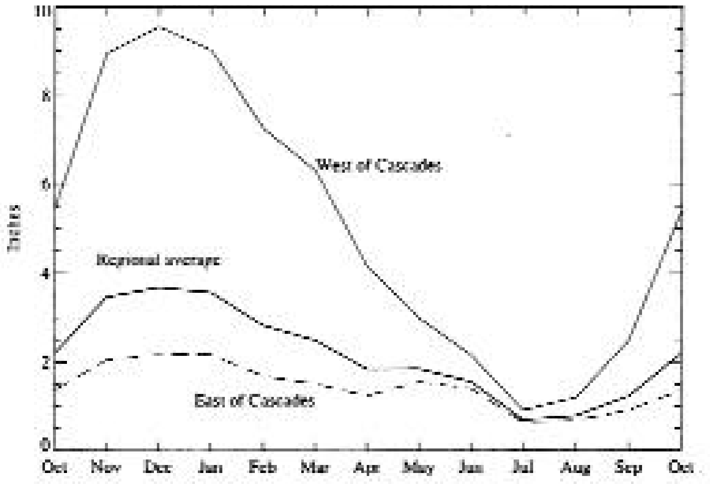
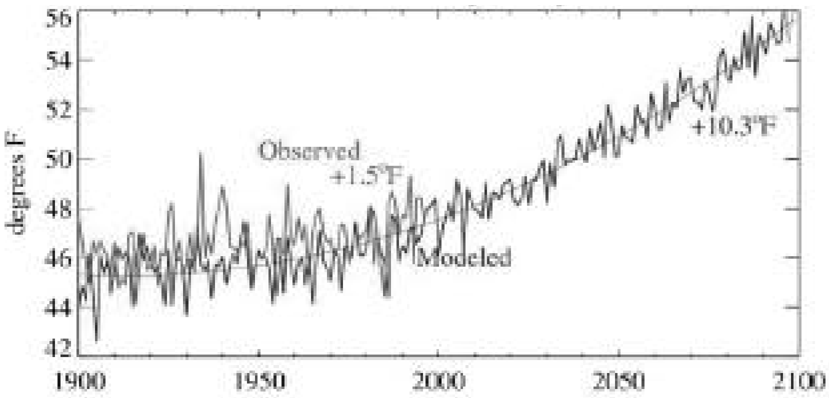


Figure 6: West of the Cascades is wetter than east, but nearly all the difference occurs in winter. Source: Mote et al. (1999), Figure 3, pg. 5.

---

[3] Analyses of Historical Climate Network data by NCDC. A similar analysis of historical trends by UW JISAO (in Mote et al., 1999) using slightly different re-weighting algorithms and regional boundaries found a 14% average precipitation increase over the 20th century. The difference between these is not significant.



Northwest Average Temperature, Observed and Modeled

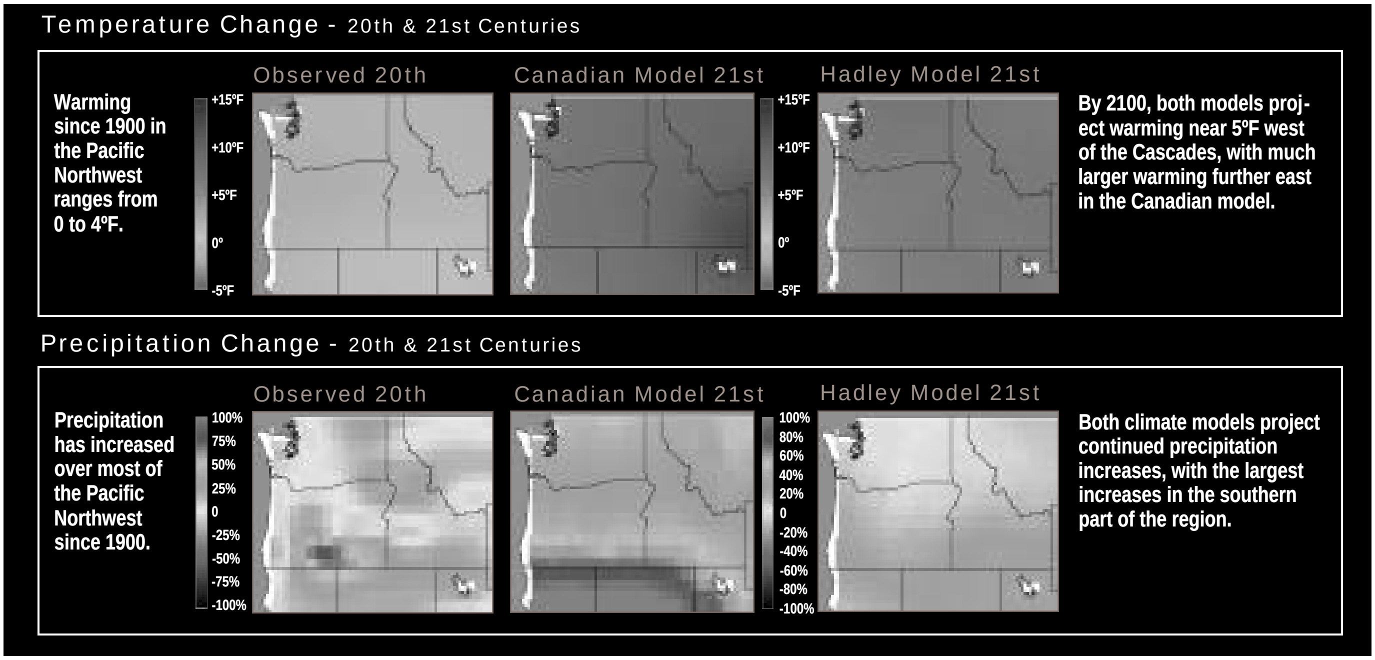
Figure 7: The red line shows annual-average temperature in the Northwest in the 20th century, observed from 113 weather stations with long records. The blue line shows the historical Northwest average temperature calculated by the Canadian model from 1900 to 2000, and projected forward to 2100. Source: Mote et al (1999), Summary (p. 6). – See Color Figure Appendix

cool phase of PDO likely occurred in the mid-1990s, but it is too early to tell with confidence. The warm phase of PDO, like El Niño,strengthens the Aleutian low, bringing warmer winter temperatures over western North America and warmer ocean temperatures along the coast. In these winters,the mid-latitude storm track tends to split,with one branch carrying storms south to California,the other north to Alaska. These winters consequently tend to be drier than normal in the Pacific Northwest and wetter than normal along the coasts to both the south and north. In contrast, years during the cool phase of PDO and during the cool,La Niña phase of ENSO are associated with a weaker Aleutian low, which tends to bring winters that are cooler and wetter than normal in the Pacific Northwest. The major exception to this cool-wet versus warm-dry pattern occurs during the strongest El Niño events,such as that of 1998. During these events,the Aleutian low is very strong and is also shifted to the Southeast, making winters on the Northwest coast warmer and wetter – i.e.,while moderate El Niños tend to make Northwest winters warmer and drier, the strongest El Niños reverse the effect on precipitation and make the region warmer but with near normal precipitation.

Scenarios of Future Climate

Projections of climate change in the Northwest were conducted through 2100 using the Canadian and Hadley models (Boer et al.,1984,1999a,b; McFarlane et al.,1992;Flato et al.,1999;Mitchell et al.,1995;Mitchell and Johns,1997; Johns et al., 1997),and through 2050 with five additional general circulation models (GCMs),two of 1998 vintage and

Temperature Change 20th and 21st Centuries



Warming since 1900 in the Pacific Northwest ranges from 0 to 4ºF.

By 2100, both models project warming near 5ºF west of the Cascades, with much larger warming further east in the Canadian model.

Precipitation has increased over most of the Pacific Northwest since 1900.

Both climate models project continued precipitation increases, with the largest increases in the southern part of the region.

Figure 8: Temperature change observed in the 20th and projected for the 21st centuries. – See Color Figure Appendix

three of 1995 vintage. In addition,one analysis linked another GCM to a regional atmospheric model,to provide a climate projection with the fine spatial resolution (1.5 kilometers, about 1 mile) necessary for hydrological studies (Leung and Ghan 1999a,1999b). In addition to the Canadian and Hadley models,the 1998 models included those developed by the Max-Planck Institut fur Meteorologie (MPI) and the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL). These four models were run using the standard emission scenario,a 1% annual increase in equivalent atmospheric CO_2 concentration with trends in sulfate aerosol loading from the IPCC IS92a scenario. The 1995 models included earlier versions from the Hadley Center, MPI,and GFDL. Compared to the 1998 group,these models included simpler representations of sea,ice, and land surfaces. It is important to note that these earlier model runs also used a different emission scenario,which did not include aerosols. The finer-scale analysis used the Community Climate Model (CCM3) of the National Center for Atmospheric Research (NCAR) driving the Regional Climate Model of the Pacific Northwest National Laboratory (PNNL-RCM). This analysis used the same scenario as the 1995 models,1% annual CO_2 –equivalent increase with no aerosols.

The coarse spatial resolution of GCMs is particularly troublesome for replicating the spatial character of climate in the Northwest,which is strongly shaped by the region's abrupt topography. Instead of the sharp Cascade crest,the models show a relatively smooth rise from the Pacific to the Rockies. Consequently, they simulate a climate for the region that is too "maritime"—milder in both winter and summer, with precipitation more evenly distributed across the region. One study comparing the Canadian model to a finer-scale regional climate model for western Canada (where GCMs have the same bias) suggested that these biases are more acute for precipitation than for temperature (Laprise et al.,1998). In projecting future climate,each model's bias relative to the present climate is removed. Despite their overall maritime bias for the Northwest,the Canadian and GFDL models (although not the Hadley model) do reproduce the Northwest region's observed 20th-century climate trends fairly well,particularly for temperature. Figure 7 shows the annual-average Pacific Northwest temperature calculated by the Canadian model through the 20th and 21st centuries,with a comparison to the observed record for the 20th century. The model matches the observed trend of the 20th century closely, and projects substantially more rapid warming through the 21st century. Figure 8 shows the changes in temperatue and precipitation over the region projected by the Canadian and Hadley models for the 21st century, and compares these to the observed pattern of changes over the 20th century.

These projections all show regional warming continuing at an increased rate in the next century, in both summer and winter. Average warming over the region is projected to reach about 3°F (1.7°C) by the 2020s and 5°F (2.8°C) by the 2050s. Annual precipitation changes projected through 2050 over the region range from a small decrease (-7% or 2") to a slightly larger increase (+13% or 4") (Hamlet and Lettenmaier, 1999),but these precipitation changes,

Table 1: Model Projections of Northwest Regional Climate

	2020s			2050s		
Model	Temp change	Precip change,inches		Temp change	Precip change,inches	
		Apr-Sep	Oct-Mar		Apr-Sep	Oct-Mar
Canadian	3.5ºF	+0.2	+3.0	5.9ºF	+0.3	+4.1
Hadley	3.2ºF	+1.3	+3.5	4.8ºF	+0.8	+2.5
MPI	3.7ºF	-0.3	+0.6	5.3ºF	-0.8	-0.4
GFDL	4.5ºF	-0.2	+0.5	7.3ºF	+0.4	+1.7
MPI 95	2.2ºF	-2.5	+0.8	4.6ºF	-1.8	+0.7
Hadley 95	2.8ºF	-1.7	+2.5	5.4ºF	-1.1	+2.5
GFDL 95	3.3ºF	+0.4	+2.7	6.1ºF	-0.8	+2.8
Average	3.1ºF	-0.3	+1.6	5.3ºF	-0.5	+1.4

Note:Results from 1995-vintage climate models were based on an emission scenario that did not include aerosols.Source:Table 3 (pg.21),Mote et al.,(1999b).

Projected Northwest Climate Change, Compared to 20th Century Variability

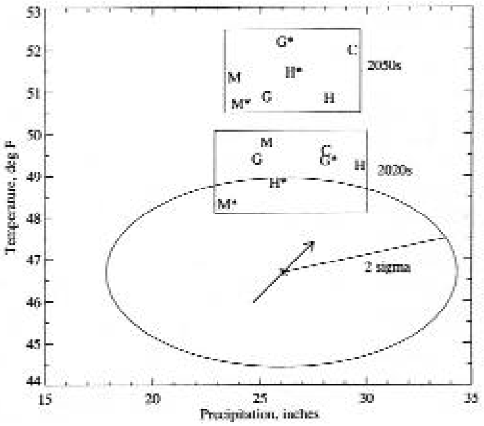


Figure 9: Climate change by the 2020s and 2050s over the Northwest Region from seven climate model scenarios. Any point on the graph shows a particular combination of regional annual-average temperature and total annual precipitation. The asterisk and arrow through it show the average climate over the 20th century and its trend, warming about 1.5°F (0.8°C) with a 2.5" (6 cm) precipitation increase. The oval illustrates how much the region's climate varied over the 20th century, enclosing all combinations of temperature and precipitation that were more than 5% likely to occur. Each letter shows one model's projection of the region's average climate, either in the 2020s or the 2050s. The models project that regional precipitation changes will lie within the range of 20th century variability, but projected temperature changes lie outside it. By the 2050s, all models project a climate so much warmer in the Northwest that it lies well outside the range of 20th century variability (*=1995-vintage model; H=Hadley; M=Max-Planck; G=GFDL; C=Canadian). Source: Regional report, Mote et al. (1999), fig. 12, pg. 19. – See Color Figure Appendix

unlike projected temperature changes,lie within the 20th century range of year-to-year variability. Projected precipitation increases are concentrated in winter, with decreases or smaller increases in summer. Because of this seasonal pattern, even the projections that show increases in annual precipitation show decreases in water availability. The 1995 and 1998 models show no systematic differences in their projections. These results are shown in Table 1,and are compared to 20th century climate variability in Figure 9. Most models by 2020,and all models by 2050,project a regional climate that is warmer than even the warmest years of the 20th century. The simulation that linked a GCM to a regional model showed similar results,with average annual warming of about 4°F (2.2°C) by 2050, wetter winters and drier summers,but showed larger seasonal differences – about 6°F (3.3°C) warming in winter and 2°F (1.1°C) in summer – due to its finer-scale representation of snow-albedo feedback (Leung and Ghan,1999a,1999b).

After 2050,the projected trend to a warmer, wetter regional climate continues in both the Hadley and Canadian models,with substantially more warming in winter than in summer in both models. By the 2090s,projected average summer temperatures rise by 7.3°F (4.1°C) in the Canadian model and 8.3°F (4.6°C) in the Hadley model,while winter temperatures rise 8.5°F (4.7°C) in the Hadley model and 10.6°F (5.9°C) in the Canadian model. Projected precipitation increases over the region range from a few percent to 20% (with a regional average of 10%) in the Hadley model,and from 0 to 50% (with a regional average of 30%) in the Canadian model.

These projected changes are associated with large-scale shifts in atmospheric circulation over the Pacific,especially in winter, which resemble the changes that occur during the strongest El Niño events. The Aleutian low is both strengthened and moved to the southeast,displacing the mid-latitude storm track southward and making the average winds on the Oregon and Washington coast stronger and more northward. Consequently, winters along the coast are warmer and wetter – both in total precipitation,and in the amount of rainfall in heavy storms,because warmer temperatures increase the quantity of water vapor the atmosphere can hold.

KEY ISSUES

Of the many potentially significant areas of climate impact in the region,the Northwest regional study selected four critical issues to examine:

Freshwater. Wetter winters are highly likely to increase flooding risk in rainfed and mixed rain/snow rivers,while year-round warming and drier summers are highly likely to increase risk of summer water shortages in rainfed,mixed,and snowfed rivers,including the Columbia. In the Columbia system,allocation conflicts are already acute,while a cumbersome network of overlapping authorities limit the system's adaptability, making it quite vulnerable to shortages.

Salmon. While non-climatic stresses on Northwest salmon presently overwhelm climatic ones,salmon abundances have shown a clear correlation with 20th century climate variations. Climate models cannot yet project the most important oceanic conditions for salmon,but the likely effects on their freshwater habitat,such as warmer water and reduced summer streamflow, are all highly likely to be unfavorable. Climate change is consequently likely to impede efforts to restore already depleted stocks, and to stress presently healthy stocks.

Forests. Northwest forests have been profoundly altered by timber harvesting and land-use conversion, both east and west of the Cascades. Whether Northwest forests will expand or contract under projected climate change, and what the effects on species mix and productivity will be, are highly likely to depend on assumptions related to plant response of water use efficiency to CO_2 enrichment, on which present evidence is incomplete. Models project several decades of forest expansion east of the Cascades and contraction to the west, with preliminary indications of larger forest contraction in the longer-term, as increased moisture stress overwhelms CO_2-induced increases in water-use efficiency.

Coasts.. Sea level rise is likely to require substantial investments to avoid coastal inundation, and abandonment of some property, especially in low-lying communities of southern Puget Sound where the land is subsiding 0.3 to 0.8 inches per decade. Other likely effects include increased risk of winter landslides on bluffs around Puget Sound, and increased erosion on sandy stretches of the Pacific Coast.

1. Freshwater

Freshwater is a crucial resource in the Northwest, and climatic effects on water resources strongly influence and couple with many other domains of impact. Despite the region's reputation as a wet place, this only applies annually to the west slopes, and even they are dry in summer. Most of the region receives less than 20 inches (50 cm) of precipitation a year, and dry summers make freshwater a limiting resource for many ecosystems and human activities. Water supply, availability, and quality are already stressed by multiple growing demands.

The Cascades largely divide rivers partly or entirely controlled by rainfall, whose flow peaks in winter, from those controlled by snowmelt, whose flow peaks in late spring. The Columbia, a snowmelt-dominated river, is one of the nation's largest, draining roughly three-quarters of the region and carrying 55-65% of its total runoff. 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 electricity, flood control, fish migration, habitat protection, water supply, irrigation, navigation, and recreation. Agriculture takes the largest share of present withdrawals, but 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 regional population growth and changing allocation priorities are intensifying competition for water. Because its watershed is so large, the Columbia's flow reflects an averaging of weather conditions over large areas and seasonal time-scales. Consequently, climatic effects on its flow can be detected and projected with more confidence than for smaller river systems, which respond most strongly to shorter-term and more local events.

Columbia basin hydrology shows a strong signal of both ENSO and PDO. Because the warm phases of these oscillations tend to make winters both warm and dry, their effects on snowpack and streamflow, and hence on regional water supply, are stronger than their effects on either temperature or precipitation. Warm-phase years accumulate less snowpack, and shift from snow accumulation to melting earlier in the season. In the Columbia, the warm phases of ENSO and PDO each reduce average annual flow by roughly 10% relative to the long-term mean, with larger reduction of peak spring flow. The effects of the two oscillations 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 the warm phase of PDO (Mote et al., 1999b, p.32). Each oscillation's cool phase has the opposite effect, bringing average stream flows about 10% higher than the mean and the highest incidence of flooding. Four or five 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.[4] When the two cycles are out of phase, streamflow tends to be near its long-term mean. A study of historical flooding in five smaller river basins found parallel results, a higher probability of flooding in both cool ENSO and cool PDO years, although the pattern was weaker than for the Columbia and not uniform. Snowmelt-dominated rivers, whose floods reflect season-long snow accumulation, showed it more than rivers with strong rainfall components, whose floods more typically reflect less predictable, individual extreme precipitation events. Moreover, the pattern was present for the likelihood but not the intensity of flooding. Still, the pattern suggests a limited ability to predict seasonal flood risk, which most management agencies in the region are not presently

---

[4] The fifth of these years was 1997, the second-highest flow year. This year's status is ambiguous, because its extreme flow is one piece of evidence for the not yet resolved claim that PDO shifted back to cool phase in the mid 1990s.

exploiting (Mote et al.,1999b,p.31 and Table 4; Jones and Grant,1996).

Understanding the effects of projected warmer temperatures, wetter winters,and drier summers on the region’s hydrology requires finer-scale analysis than GCMs alone can provide. To obtain this,two analyses were conducted linking a GCM projection to finer-scale models. In an analysis of snowpack for the entire Northwest region using the PNNL-RCM model described above,projected snowpack declined about 30% over the Northern Rockies and 50% over the Cascades by roughly 2050,the time that CO2 concentration had doubled (Leung and Ghan,1999a,1999b). Projected rise of the snowline and earlier spring melt are corroborated by broadly similar results from earlier GCM-driven studies of fine-scale hydrology models elsewhere in the American West (Giorgi and Bates,1989;Giorgi et al., 1994;Matthews and Hovland,1997). In a separate study of the Columbia basin alone,several climate models were used to drive detailed models of hydrology, and dam and reservoir operating rules, allowing an integrated examination of interactions between natural and managed responses to climate change. A striking result of these simulations was widespread loss of moderate-elevation snowpack,as Figure 10 shows. Typical snowcover on March 1 in the 2090s is projected to be about equal to present snowcover on in mid-May, although deep snowcover in the upper basin still persists through June.

Projected Reduction in Columbia Basin Snowpack

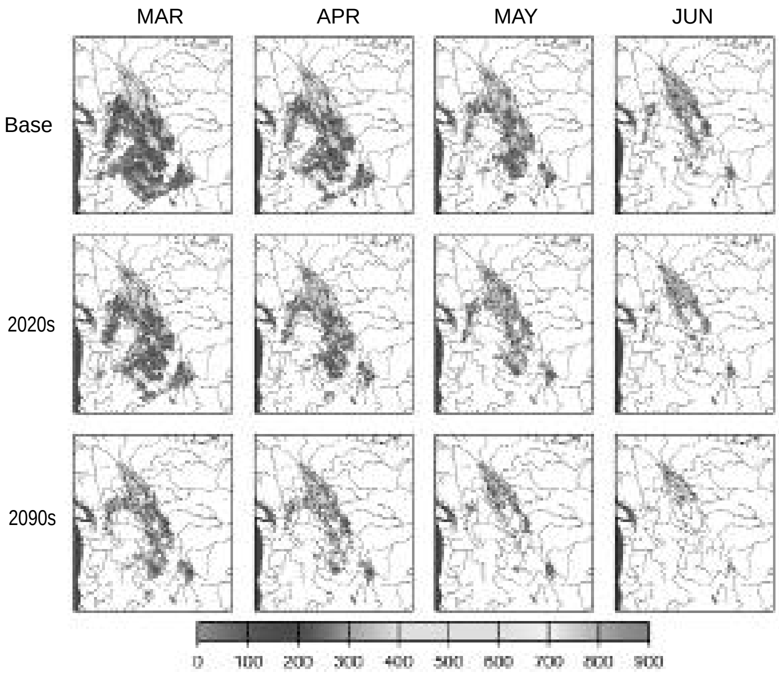


Figure 10: By the 2090s, projected Columbia Basin snowpack on March 1 will be only slightly greater than present snowpack on June 1. Simulations use the VIC hydrology model under the Hadley scenario. Units in millimeters. Source: Hamlet and Lettenmaier, 1999. – See Color Figure Appendix

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. Both precipitation and temperature matter. 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. When changes in temperature and precipitation are considered separately, temperature — which climate models project with greater confidence than precipitation — has the larger effect on streamflows (Mote et al.,1999b, Figure 28;Nijssen et al.,1997).

While all the climate models studied agree on these seasonal effects on Columbia streamflow, they differ in the relative size of winter and summer changes, and consequently in whether total annual flow increases or decreases. Projections for annual flow in the 2020s in four models range from a 22% increase to a 6% decrease,with a mean 5% increase; for the 2050s,projected changes range from a 10% increase to a 19% decrease,with a mean 3% decrease. Figure 11 illustrates the range of projected seasonal flow shifts for all seven models in the 2050s.

To assess the socioeconomic effects of these changes in stream flow, a reservoir operations model was used to project how the reliability of different water-management objectives (i.e.,the probability of meeting the objective in any year) changes under climate change. The model was first used to examine how present climate variability affects reliability of five uses,under two different sets of system operation rules:present rules,under which the practice is to grant highest priority to ensuring availability of hydroelectric energy sold on “firm”contracts,[5] and a set of alternative,“fish-first” rules that would give highest priority to maintaining minimum flows to protect fish. The effect of alternative operation rules for the system is to distribute risks of shortage among uses. The results showed that reliability is high for all objectives in favorable,high-flow years (i.e.,cool PDO/La Niña years) and that one top-priority objective can be maintained at or near 100%

---

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

reliability even in unfavorable,low-flow years (i.e., warm PDO/El Niño years),but that other uses suffer large reliability losses in unfavorable years. For example,the reliability of both the fish-flow objective under present rules,and the firm energy objective under "fish-first" rules, fall to about 75% in warm PDO/El Niño years.(Mote et al.,1999b, figure 32) Of the five objectives considered,the most sensitive 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,section 2.4.2,pp.39-41.)

Though projected changes in total annual flows are relatively small,the projected seasonal shifts are likely to bring large effects. Smaller, rainfed,and mixed rain/snow basins on the west slope are already susceptible to winter flooding,and have significantly increased risk of flooding in the wetter winters of La Niña years (Mote et al.,1999b,Table 4). The historical severity of flooding,which is more influenced by single extreme events and less by season-long precipitation,shows no such climate signal. Projected warmer, wetter winters are likely to bring further increases in winter flooding risk in these basins, while continuing growth in coastal population will very likely increase the property vulnerable to such flooding. Impacts on human health are also possible, particularly where urban storm-sewer systems are inadequate to handle the increased runoff. No systematic assessment of changes in westside winter flooding risk under climate change,and potential consequences for property damage and human health,has yet been conducted.

Projected Seasonal Shift in Columbia River Flow

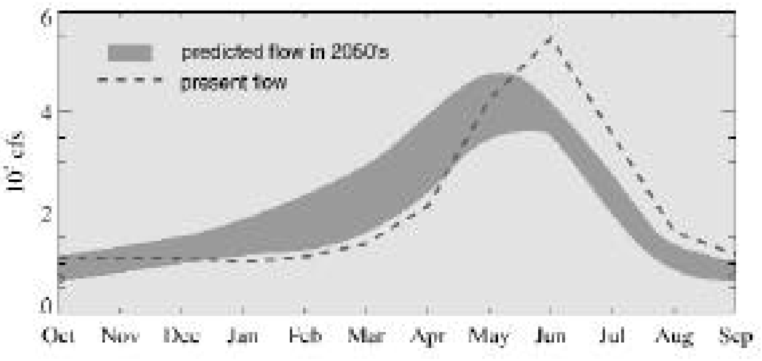


Figure 11: While only small changes are projected in annual Columbia flow, seasonal flow shifts markedly toward larger winter and spring flows, and smaller summer and fall flows. The blue band shows the range of projected monthly flows in the 2050s under the Hadley and Canadian scenarios and the two other 1998-vintage climate models used in the Northwest assessment (MPI and GFDL). Source: Mote et al. (1999), Summary, Figure 7. – See Color Figure Appendix

In contrast,in large,snowmelt-dominated systems like the Columbia, even large increases in winter flows pose little increased risk of flooding,since existing management systems are adequate to respond to floods and even the highest projected winter flows remain well below present spring peaks. But the system is much less robust to low flows than high. Reduced summer flows are likely to bring substantial reductions in both hydropower and freshwater availability by mid-century, exacerbating already-sharp allocation conflicts driven by population growth, expansion of irrigated farmland,and increasing priority for maintaining salmon habitat (Cohen et al.,1999).

Projections of changes in reliability for six objectives under present operational rules,using two climate models for the 2020s,and one for the 2090s,are shown in Table 2 (Hamlet and

Table 2: Changes in Reliability of Various Columbia Management Objectives, Assuming Present Operating Rules.

Source:Mote et al.(1999b),Table 6.

		2020s		2090s
Objective	Base Case	Hadley	Max-Planck	Hadley
Flood Control	98%	92%	96%	93%
Firm Energy	100%	100%	98%	99%
Non-firm Energy	94%	98%	87%	90%
Snake River Irrigation	81%	88%	76%	75%
Lake Roosevelt Recreation	90%	88%	79%	78%
McNary Fish Flow	84%	85%	79%	75%

Lettenmaier, 1999). Under present rules, reliability of firm energy is projected to remain near 100%, while other uses suffer reliability losses up to 10%, similar to the effect of PDO. The effects of rule changes, which will interact with both climate change and variability, are likely to be even larger. For example, "fish-first" rules would reduce firm power reliability by 10% even under present climate, and by 17% in warm-PDO years. Adding the projected long-term climate trend would very likely reduce reliability even more, but these interactions have not yet been quantified.

Increasing stresses on the system are highly likely to coincide with increased water demand, principally from regional growth but also induced by climate change itself. For example, an analysis of Portland's municipal water demand for the 2050s projected

Yakima Valley Irrigated Agriculture: Rigidity and Vulnerability

The Yakima Valley in south central Washington is one of the driest places in the United States, and contains some of its most fertile farmland. With annual precipitation of only about seven inches, the valley produces annual agricultural revenue of $2.5 billion, with the largest share from tree fruit. Fully 80% of the farmed area of 578,000 acres is irrigated. The basin's hydrology is strongly snowmelt-dominated with its main reservoirs in the mountains. With reservoir capacity equal to about half of annual demand, the region can tolerate a moderate one-year drought. Most farmers also have wells and pump groundwater in times of shortage, subject to state permits.

Drought in the valley, agricultural expansion, and water policy have all followed the PDO cycle. Water shortages have occurred eight times since 1945, all but once in warm-PDO years. Moreover, during the last cool phase (1945-1976) expectations of continued abundance of water led to sharp expansion of agriculture. In the subsequent warm phase farmers experienced substantial hardships, but nearly no contraction occurred. The first major decision allocating water among users was made in 1945, at the end of a warm phase period. Thereafter, no further controls were enacted until after 1979, when the warm phase had returned (Glantz, 1982). Shortage years since then have seen many hundreds of new wells dug, under emergency state permits that typically allow pumping only for the duration of the drought.

Several economic and institutional factors systematically increase the valley's vulnerability to drought. Division of water-right holders into "senior" users (who receive their full allocation every year) and "junior" users (who bear all risk of shortages) imposes large losses on junior users in shortage years – e.g., a 63% proration of water allocation and $140 million of losses in 1994 — and gives strong incentives for unsustainable pumping, depleting the region's groundwater and perpetuating the myth that the region has enough water. A progressive shift from annual crops to more lucrative perennials, such as tree fruit, grapes, and hops, has further exacerbated vulnerability: the perennials consume more water, reduce farmers' flexibility to alter their planting for projected dry years, and put many years' investment at risk from a single drought, further increasing incentives to pump groundwater. Some promising initiatives to improve management of the region's water are underway, including state-subsidized investments to increase efficiency of junior users' irrigation systems, and a novel partnership between one junior and one senior irrigation district, but the valley still lacks a coherent basin-wide drought strategy. Moreover, if PDO is now re-entering its cool phase, making continuance of the ample supplies of the past two years likely, the region is likely to face renewed pressure to expand irrigated cropland. As happened during previous cool-PDO periods, such expansion would further increase the region's vulnerability to future recurrence of dry conditions (Gray, 1999).

Figure 12: Irrigated agriculture in the Yakima Valley, where annual precipitation is about seven inches. Source: P. Mote, University of Washington

that climate change would impose an additional 5-8% increase in total summer demand (5% - 10% in peak day demand) on top of a 50% increase in summer demand from population growth (Mote et al., 1999b,section 2.4.3,p.43). Such climate-related demand increase,which is also highly likely for other demands such as electric generation,irrigation,and salmon habitat preservation, would compound the climate-related supply decreases discussed above. Further assessment is required to quantify risks of shortfall under the interaction of regional growth, climate-driven demand increase, and climate-driven shifts in seasonal supply.

Adaptation Options

While the Columbia's infrastructure and institutional authority are able to manage high flows,at least up to some fairly high thresholds (Hamlet and Lettenmaier, 1999;Miles et al.,2000),the means for dealing with low flows are rigid and inadequate.

Seattle Public Utilities: Learning From Water Shortages

Seattle Public Utilities (SPU) experienced summer droughts and potential shortages in 1987,1992,and 1998. Its responses to the three events illustrate institutional flexibility and learning. Summer 1987 began with full reservoirs,but a hot dry summer and a late return of autumn rains created a serious shortage in which water quality declined,inadequate flows were maintained for fish,and the main reservoir fell so low that an emergency pumping station had to be installed. In response,the City developed a plan to manage anticipated shortages with four progressive levels of response:advising the public of potential shortages and monitoring use; requesting voluntary use reductions;prohibiting inessential,high-consumption uses such as watering lawns and washing cars;and rationing.

Another drought came in 1992, following a winter with low snowpack but during which SPU had spilled water from its reservoirs to comply with flood-control rules. With a small snowmelt, reservoirs were low by the spring,and SPU invoked mandatory restrictions during the hot dry summer that followed. The resultant low demand 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.

Figure 13: Since 1992, Seattle Public Utilities has used information on year-to-year climate variability to help guide its seasonal forecasting and reservoir operations." Source: Seattle Public Utilities.

Their regrettable spilling of early 1992 alerted SPU to the risks inherent in following rigid reservoir rule curves. Since then,they have 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,they 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 integrating seasonal forecasts into its operations,SPU is an uncommonly adaptable resource-management agency. But it still has a long way to go in adapting to longer-term climate variability and change. SPU presently projects that new conservation measures will keep demand at or below present levels until at least 2010,while conservation measures and planned system expansion (including a connection with a neighboring system) will maintain adequate supply until at least 2030 (A.Chinn,Seattle Public Utilities,personal communication,2000). Over this period, climate change is likely to have significant effects on both supply and demand,but is not yet included in planning. The warmer drier summers projected under climate change are likely to stress both supply and demand, requiring earlier capacity expansion and triggering the more restrictive conservation provisions more often (Gray, 1999). Moreover, it is possible that the recently suggested shift to cool PDO could mask this effect for a couple of decades, risking sudden appearance of shortages when PDO next shifts back to its warm phase.

The Pacific Northwest Coordinating Agreement, charged with allocating water under scarcity on the basis of defined priorities,is a weak and fragmented body with no one clearly in charge – Idaho is not even a member. Moreover, the persistence of the prior appropriation doctrine under western water law rigidly maintains large allocations to low-value uses,hindering attempts to rationalize use under present and increasing scarcity.

Managing under projected future scarcity is highly likely to require some combination of reducing demand,increasing supply, and reforming institutions to increase flexibility and regional problem-solving capacity. Demand for water can be reduced through various technical means (e.g.,more efficient irrigation methods, changes in agricultural land management,or high-efficiency plumbing fixtures in new construction) and through various policy approaches (e.g.,tax incentives for conservation investments, revision of rate structures). The most promising approaches to encourage conservation, however, would be development of institutions to allow reallocation of water to higher-value uses,particularly in times of shortage. Although the barriers to such a major shift of ownership rights are formidable,the Northwest could gain insights from prior western experience with water banks and contingent marketing (Huffaker,Whittlesey, and Wandschneider, 1993;Miller, 1996;Miller, Rhodes, and MacDonnell,1997). Supply can likewise be increased through various technical and policy means,such as developing groundwater sources or using groundwater recharge for water storage; improving system management by using seasonal climate forecasts (Callahan et al.,1999);promoting optimal use of existing lower-quality supplies,e.g., by delivering reclaimed non-potable water for some uses;or developing non-hydro electric generating capacity;or if permitted by both governments,negotiating water purchase from Canada.

Increasing institutional flexibility is an essential component of response,but is rendered difficult by the fragmentation of the current system. In a survey of water managers on their use of climate forecasts in planning,most stated that they had limited flexibility to use even ENSO forecasts to take advantage of predictably higher-flow years,and most were completely unaware of PDO, whose effect on flows appears to be as large as that of ENSO (Mote et al., 1999b,Section 2.5.3,pp.47-49.). Indeed,long-term assessment of institutional responses suggests that in at least some cases, responses have served to increase, rather than decrease,vulnerability to interdecadal variability (see Yakima Valley box). Moreover, long-term climate change is not yet used in planning decisions, even for investment in infrastructure with expected lifetimes of many decades.

2. Salmon

Salmon are anadromous fish,meaning that they swim upstream 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 species,then swim downstream to the ocean. Most species make this trip in spring or early summer, taking advantage of the high streamflows that accompany peak spring melting (in snowfed rivers) and arriving at roughly the onset of coastal and estuarine upwelling that fuels marine food-chain productivity. In the ocean the salmon grow to adulthood and live for several months to six years before returning to their spawning grounds. Most die in their natal streams after spawning,thereby delivering marine-derived nutrients that are now recognized as important inputs to stream and riparian ecosystems.

Northwest salmon stocks have been highly stressed for decades by intense fishing pressure and threats to their stream habitats including urbanization,sedimentation and pollution of streams, wetland draining,and dam building. Construction of the Grand Coulee and Hell's Canyon dams eradicated all salmon stocks above these points on the Columbia and Snake Rivers respectively. Fish ladders on other dams are only partly effective at allowing fish to pass,and dams also degrade salmon habitat by changing free-running rivers into chains of lakes, warming in-stream temperatures, reducing dissolved oxygen,and altering sediment loads.

These factors have brought regional salmon stocks to widespread decline (Myers et al.,1998),despite massive efforts to restore habitat and to supplement wild stocks with hatcheries,which reflect salmon's status not just as a commercially important fish but as a regional cultural icon. 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. The decline is not universal:populations from coastal rather than interior streams,from more northerly ranges,and with relatively short freshwater rearing periods have fared better than others. In many cases,the populations that have not declined are now composed largely or entirely of hatchery fish (National Research Council,1996;Beechie et al., 1994;Bottom,1995).

In March 1999, eight new salmon stocks were listed under the Endangered Species Act (ESA) as threatened and one as endangered, bringing the number of salmonid stocks listed to 26. The new listings included Puget Sound Chinook, the first-ever ESA listing of a species inhabiting a highly urbanized area. Just as prior listings of Columbia and coastal Oregon stocks severely constrained forest and water management, it is possible that the impacts of this new listing on the Seattle economy will be large, but it will be some years before these impacts are known (Klahn, 1999).

Salmon are sensitive to various climate-related conditions, both inshore and offshore, at various times of their life cycle. Eggs are vulnerable to stream scouring from floods, and migrating juveniles must make the physiological transition from fresh to salt water and require food immediately on reaching the ocean. According to a long-standing but unconfirmed hypothesis, their fate is keenly sensitive to the timing of their arrival relative to the onset of summer northerly winds and the resultant upwelling of nutrient-rich deepwater and spring phytoplankton bloom: either too early or too late, and their survival is imperiled from insufficient food (Pearcy, 1992). More recently, it has been suggested that their survival is predominantly controlled by the balance between predator and baitfish populations at the time of their arrival, which determines predation pressure on salmon (Emmet and Brodeur, 2000).

Although the relative contributions of and interactions between climate and non-climate factors, and inshore and offshore conditions are highly uncertain, salmon stocks throughout the North Pacific show a strong association with PDO (Figure 14) (Hare et al., 1999; Mantua et al., 1997; Francis, 1997; Francis et al., 1998; Reeves et al., 1989). Salmon in the Northwest are more abundant in the cool PDO phase, less abundant in the warm phase, while Alaska salmon show the opposite pattern. When the PDO shifted from cold to warm in 1977, catches in the Northwest dropped sharply while Alaskan catches soared.[6] The mechanisms for this observed climate effect on stocks are poorly known, and probably include some effects of both freshwater and marine changes. It is speculated that coastal waters off Washington and Oregon during the warm phase are warmer and more thermally stratified, and consequently poorer in nutrients. 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 warm-water conditions over several years. 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 (Pinnix, 1998).

Salmon Catches and Inter-decadal Climate Variability

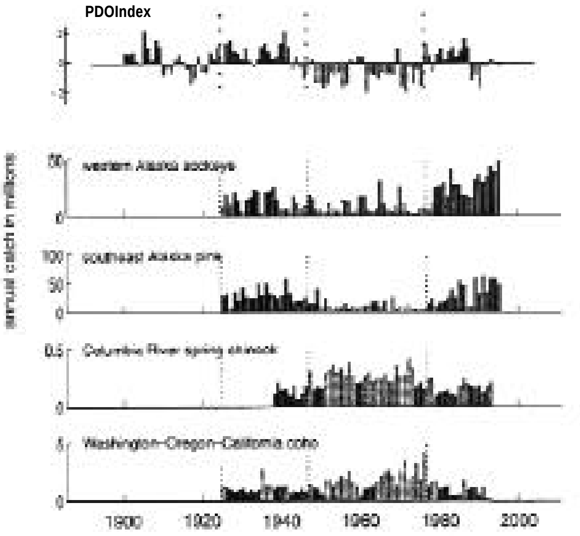


Figure 14: 20th century catches of Northwest and Alaska salmon stocks show clear influence, in opposite directions, of the Pacific Decadal Oscillation. Source: Mote et al. (1999), Figure 36, pp. 56. – See Color Figure Appendix

Climate models presently lack the detail to project changes in many specific factors in the marine environment 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 more informative, in salmon's inshore and estuarine habitats, their projections are uniformly unfavorable. Increased winter flooding, reduced summer and fall flows, and warmer stream and estuary temperatures are all harmful for salmon (Baker et al., 1995; Bottom, 1995. Earlier snowmelt and peak spring streamflow will likely deliver juveniles to the ocean before there is adequate food for them, unless the onset of summer northerly winds is also advanced under climate change, but climate models cannot yet address this question. One study has suggested that oceanic warming from even a CO_2 doubling may push the range of some salmon north out of the Pacific entirely (Welch et al., 1998), although recent studies suggest the notion of direct ocean

---

[6] Catches are a good indicator of stocks, because catch variation since the 1930s is almost entirely due to stock fluctuations, not variation of fishing effort (Beamish and Bouillon, 1993)

Figure 15: Old-growth Ponderosa Pine forest with open, grassy understory near Bend, Oregon. Source: S. Garrett and the McKay Collection, Bend, OR.

thermal limits to salmon survival is too simplistic (Emmet and Schiewe,1997;Bisbal and McConnaha, 1998;Hargreaves,1997). 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,suggests that the effect of ocean temperature on salmon is not primarily direct,but operates through changes in food supply (Walker et al.,1999; Pearcy et al., 1999).

Salmon are already beset with a long list of man-made problems,to which climate change is a potentially important addition. At sea, fishing pressure has recently been sharply curtailed,but wild salmon face intense competition from hatchery fish,some of which are being released at ten times the rate of natural smolt migrations. Onshore,the effects of present climate variability on salmon in streams are swamped by clear-cutting, road building,and dams. The effects of future climate 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. If endangered-species listings and public concern prompt a strong restoration response,it would likely take the form of far-reaching restrictions on land use near rivers and streams. Such measures would very likely have far-reaching social and economic impacts,which could greatly exceed the direct effects of decreases in salmon abundance.

Adaptation Options

At present,the only climatic effects on salmon that are sufficiently understood to allow an informed response involve warming of streams (McCullough, 1999). Maintaining forest buffers for shade along banks and operational changes on managed rivers can reduce present warming (about 4.5º F, largely due to dams) (Quinn and Adams,1996),and could potentially slow future warming under climate change,although such measures would ultimately be overwhelmed by continued climate warming. Though other mechanisms of climatic effect are less known,observed fluctuations of stocks with PDO suggest applying a conservative bias to allowable-catch decisions during warm-PDO years. Measures to reduce general stress on stocks,such as changing dam operations to provide adequate late-summer streamflows,might increase salmon's resilience to other stresses,including climate,although maintaining such flows is highly likely to become increasingly difficult under regional warming that shifts peak streamflows to earlier in the year. More forceful measures would include removing existing dams,as now proposed for four dams on the lower Snake River, and accepting the resultant reduced ability to manage summer water shortages. Salmon have evolved a great diversity of life histories and behaviors to thrive in a highly variable and uncertain environment. Maintaining that diversity, which is highly likely to require even greater efforts to preserve healthy, complex freshwater and estuarine habitat,is likely among the most effective options to enhance salmon's resilience to climate change.

3. Forests

Evergreen coniferous forests dominate the landscape of much of the Northwest. In the west,coniferous forests cover about 80% of the land,including some of the world's largest trees and most productive forests,and about half the world's temperate rainforest. Belying their lush appearance,on most sites these forests are constrained by moisture deficit during the warm dry summers,which limits seedling establishment and summer photosynthesis,and creates favorable conditions for insect outbreaks and fires (Agee,1993; Franklin,1988). Forests of the dry interior operate under an even more severe summer soil-moisture deficit (Law et al.,1999),which is consequently the dominant factor controlling the species distribution and productivity of forests throughout the region (Zobel et al.,1976;Grier and Running, 1977;Waring and Franklin,1979;Gholz,1982).

Forests throughout the Northwest have been profoundly altered by human intervention over the past 150 years. West of the Cascades, forests have been cleared for conversion to other land uses or clearcut for timber and replanted, replacing massive old-growth forests with young, even-aged managed forests. By various estimates,75 to 95% of original old-growth forest has been logged,and much of what remains is in small fragmented stands (Mac et al.,1998,p.646). The transition is estimated to have released to the atmosphere 2 billion metric tons of carbon over the century (Harmon et al.,1990). East of the Cascades,decades of intensive grazing, fire suppression,and selective harvesting of mature trees have transformed the former open,park-like forest of ponderosa pine,Douglas fir, and western larch into a dense mixed forest overstocked with shade-tolerant pines and firs. The new forest mix is highly susceptible to insect outbreaks,disease and catastrophic fire (Mason and Wickman,1988; Lehmkuhl et al.,1994). Of the ponderosa pine forest that formerly comprised three quarters of eastside forests,more than 90% has been logged or lost (Figure 15). While the former open forest structure was maintained by frequent,low-intensity fires (in contrast with western forests,whose natural regime was of catastrophic fires at intervals of several centuries), fire suppression in the east has allowed large accumulation of fuel. These high fuel loads increase the risk of extreme fires that replace stands over large areas (Quigley et al.,1996). The effects of these human activities overwhelmed climatic effects on Northwest forests during the 20th century, and continued forest management is highly likely to interact strongly with climate effects during the 21st century.

Tree Growth and Inter-Decadal Climate Variability

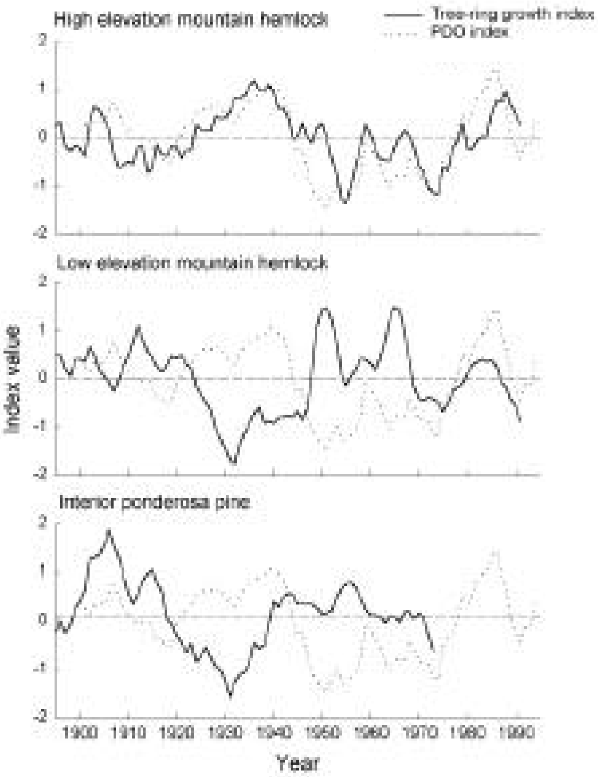


Figure 16: Trees near their climatic limits show strong signals of inter-decadal climate variability. Those near the upper treeline grow best in warm-PDO years because snowpack is lighter, while those near the dry lower treeline grow worst in warm-PDO years, because of summer moisture deficit. Source: Peterson and Peterson, 2000.

Tree growth can show a clear effect of climate variability (which is why tree rings can provide a useful record of past climate),most pronounced in stands near their climatic limits,e.g.at the upper (cold) or lower (hot and dry) timberline. Figure 16 shows the effect of 20th century climate variability on three Northwest conifer populations,one at high and two at low elevation (Peterson and Peterson,2000). Near the upper timberline,where trees are not moisture-constrained, growth shows strong positive correlation with PDO. This is because positive PDO periods tend to have lighter snowpack and consequently an earlier start to the high-elevation growing season,promoting tree growth and upward expansion of forests to colonize sub-alpine meadows (Franklin et al.,1971;Rochefort et al.,1994). Near the lower timberline,the opposite relationship is present. Growth is negatively correlated with PDO, because the warm dry winters and light snowpack of positive-PDO periods increase summer drought stress,which is the limiting factor at these elevations (Little et al.,1994; Peterson,1998). In other regions,such as intermediate elevation stands in the interior, and the western hemlock and pacific silver fir zones west of the Cascade crest,present climate variations have little discernible influence on the structure and composition of most mature stands,which – once established – have substantial ability to buffer themselves against climate variation. In such stands,competition and other factors obscure present climate signals in individual trees (Brubaker, 1986;Dale and Franklin,1989).

The principal effect of climate on these forests has come not through direct effects but indirectly, through changes in disturbance by fire,insect infestation,and disease (Overpeck et al.,1990; Fosberg et al.,1992;Ryan,1991). Major disturbances can reset forests to their establishment stage,when trees are the most sensitive to adverse environmental conditions (Gardner et al.,1996). For insect and disease

Annual Northwest Area Burned in Forest Fires over the 20th Century

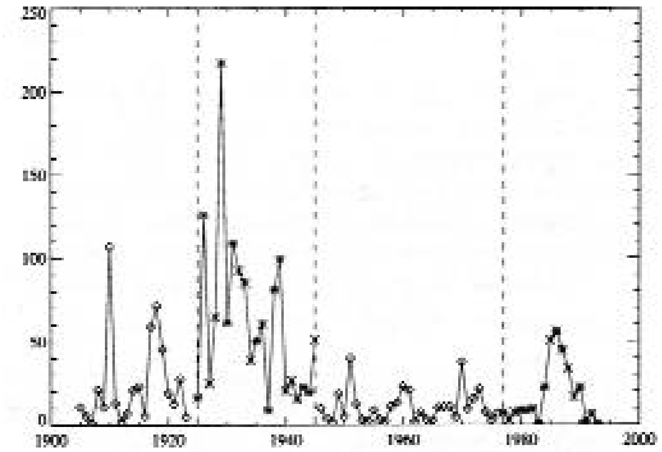


Figure 17: Prior to modern fire suppression, annual Northwest area burned in forest fires showed a clear association with inter-decadal climate variability. Dashed lines show PDO regime shifts. Source: Mote et al. (1999), p. 65.

Projected Northwest Vegetation Changes under two Ecosystem Models, 2100

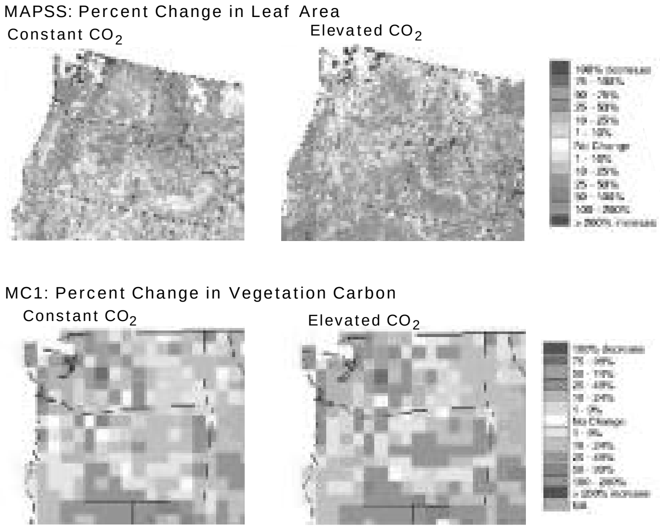


Figure 18: Under the Hadley scenario, the MAPSS (top row) and MC1 (bottom row) models project expansion of forests east of the Cascades and contractions to the west, assuming increased water-use efficiency under elevated atmospheric CO_2 (right column). When no such increase is assumed (left column), projections are nearly unchanged in the MC1 model, but change to a large contraction region-wide in the MAPSS model. Source: Bachelet et al (2000). – See Color Figure Appendix

mortality, the available 20th-century data are inadequate to quantify the region-wide effects of climate variability, but smaller-scale studies have shown strong correlations of both bark beetle and defoliator outbreaks with severe drought conditions (Swetnam and Lynch,1993). For fire,total Northwest forest area burned shows a significant region-wide association with PDO and with the Palmer Drought Severity Index,especially before the introduction of widespread fire suppression. For example,as Figure 17 shows,the warm-PDO period of 1925-1945 had much more area burned than the cool-PDO periods immediately preceding and following it (Mote et al.,1999a). The effect of ENSO on fire is less clear. In contrast with the strong ENSO signal observed in wildfire in the Southwest US (Swetnam and Betancourt,1990),no region-wide effect is evident in the Northwest. At smaller scales, however, one study of historical fire data and ongoing tree-ring studies suggest a significant ENSO effect (Heyerdahl 1997;T. Swetnam,personal communication,1999).

Under projected future climate change,the effect on Northwest forests is highly likely to reflect complex interactions between several factors,some of which vary with particular sites. The direct effect of projected warmer summers without substantial increase in rainfall would be to increase summer soil moisture deficit, resulting in reduced net photosynthesis and tree growth,increased stress and tree mortality, and decreased seedling survival. Reduced snowpack has different effects at different sites:it extends the growing season and facilitates seedling establishment where snowpack is presently heavy, but reduces growing-season moisture availability and consequently increases drought stress in dry areas (Peterson,1998). One early empirical study used observed associations between existing forest communities and local climate to project impacts of future climate change on Northwest forests. This study projected that forested area in the Northwest would contract,principally through forest dieback and sagebrush-steppe expansion at the dry lower treelines east of the Cascades (Franklin et al.,1991).

It is likely, however, that the effects of increased summer drought will be offset to some degree by wetter winters,or by the direct effects of elevated atmospheric CO_2 concentration. Though drought stress occurs in late summer, its severity depends principally on winter and spring precipitation, because forests rely on moisture stored seasonally in deep soil layers to offset summer water deficits. Under climate model projections,the forest growing season begins several weeks earlier in the spring than at present,making some increased winter precipitation immediately available to forests. Beyond this water put to use immediately, wetter winters could mitigate summer drought stress still further, if the soil has enough storage capacity to hold the additional water until it is needed in the late summer. Although there are some indications that Northwest forest soils below the snow line are already fully recharged under present winter rains, so precipitation increases would be lost as runoff (Harr, 1977; Jones and Grant,1999; Perkins,1997), the advance of growing season makes the significance of these results for seasonal water storage under climate change ambiguous (Bachelet et al., 1998). Elevated CO_2 concentration may also possibly mitigate productivity losses from summer drought stress, by increasing photosynthetic efficiency or – likely more important in water-limited Northwest forests – by increasing trees' water-use efficiency through reduced stomatal conductance. Laboratory and field studies have shown increases in both net carbon uptake and water-use efficiency in many plants (Bazzaz et al.,1996),but most such studies have examined agricultural crops, grasses,or tree seedlings. The evidence available on mature trees is quite limited.One experimental study in a young pine plantation in North Carolina found that elevated CO_2 brought increased carbon assimilation with no change in water use - an increase in water-use efficiency, but not through the expected mechanism of increased stomatal resistance (Ellsworth, 1999).The applicability of this result to projecting responses of mature connifer forests in the more moisture-stressed Northwest remains unknown. Cool coniferous forest systems appear to be among the least responsive in aggregate to elevated CO_2 (Ellsworth,1999;Mooney et al.,1999).

Process-based models are needed to represent and quantify these effects,because empirical studies can only observe forests' responses to the present range of climatic conditions with present CO_2 concentration (VEMAP Members,1995). With assumptions of increased water-use efficiency, ecological models driven by the Hadley, Canadian,and other climate-change scenarios project opposite effects east and west of the Cascade Crest. Cool coniferous forests to the west are projected to 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 to the east are projected to expand,with increases in vegetation carbon or leaf area also exceeding 50% in some locations (Neilson and Drapek,1998;Daly et al.,2000;Neilson et al.,1998). The increases in the east are relative to a smaller present biomass,and so are smaller in absolute terms. While these model results reflect substantial recent progress,they have significant remaining weaknesses and uncertainties. For example,none adequately represents fog,which can comprise as much as half the water input to forests on some coastal and hillside sites. Moreover, results of different models in the Northwest differ strongly in their sensitivity to the water-use efficiency assumption. When no increase in efficiency is assumed,model results range from a very similar pattern of expansion in the east and contraction in the west,to a region-wide contraction that resembles the projection of the earlier empirical analysis (Bachelet et al.,2000).

The magnitude and consequences of future changes in water-use efficiency represent the most important uncertainties in projecting the climate response of Northwest forests over the next century. While the balance of preliminary evidence suggests at most a small water-use efficiency increase in Northwest coniferous forests due to enhanced CO_2, model results differ substantially in whether the effect of this unknown on the extent,density, and species distribution of Northwest forests is large or small. Over the longer term,there are preliminary

Northwest Forest Fire Projections

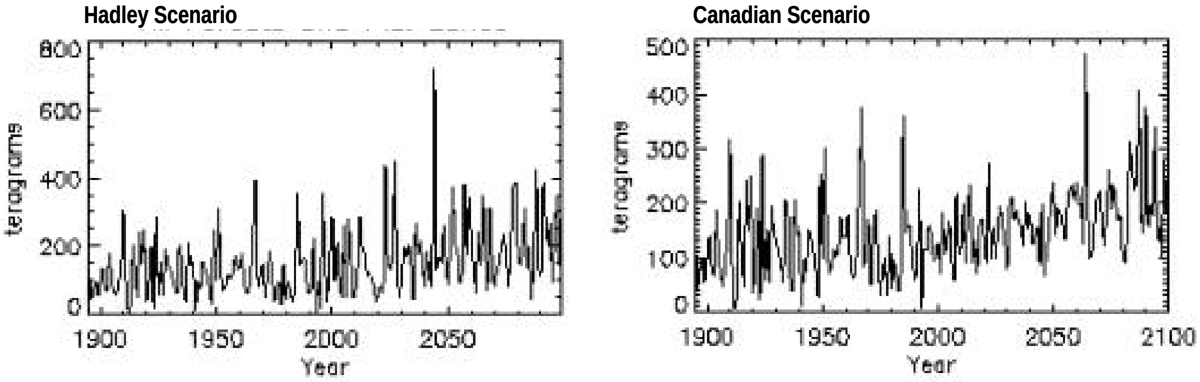
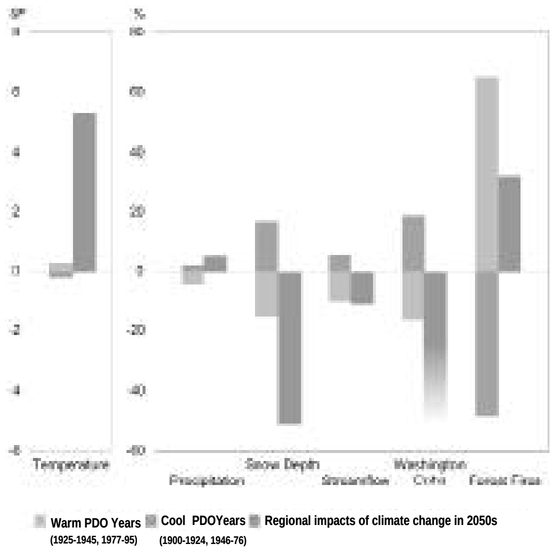


Figure 19: The MC1 ecosystem model projects substantial increases in the amount of forest biomass burnt annually in the Northwest under both the Hadley and Canadian scenarios. Source: Bachelet et al. (2000)



Temperature	**Change in annual average regional temperature (ºF)**
Precipitation	**Change in annual average regional precipitation (%)**
Snow depth	**Change in average winter snow depth at Snoqualmie Pass, WA (%)**
Streamflow	**Change in annual streamflow at The Dalles on the Columbia River (corrected for changing effects of dams) (%)**
Salmon	**Change in annual catch of Washington Coho salmon (%)**
Forest fires	**Change in annual area burned by forest fires in WA and OR (%)**

Figure 20: This chart compares possible Northwest impacts from climate change by the 2050s with the effects of natural climate variations during the 20th century. The orange bars show the effects of the warm phase of the Pacific Decadal Oscillation (PDO), relative to average 20th century values. During warm-PDO years, the Northwest is warmer, there is less rain and snow, stream flow and salmon catch are reduced, and forest fires increase. The blue bars show the corresponding effects of cool-phase years of the PDO, during which opposite tendencies occurred.

The pink bars show projected impacts expected by the 2050s, based on the Hadley and Canadian scenarios. Projected regional warming by this time is much larger than variations experienced in the 20th century. This warming is projected to be associated with a small increase in precipitation, a sharp reduction in snowpack, a reduction in streamflow, and an increase in area burned by forest fires. Although quite uncertain, large reductions in salmon abundance ranging from 25 to 50%, are judged to be possible based on projected changes in temperature and streamflow. Source: based on Mote et al., 1999, pp. 27. – See Color Figure Appendix

indications that,increased evapotranspiration under warmer temperatures could possibly overwhelm even the largest assumptions of increased water-use efficiency, leading to substantial forest dieback.

The largest effects of future climate variability or change on Northwest forests are likely to arise from changes in disturbances (McKenzie et al,1996;Torn and Fried,1992). Two dynamic vegetation models now incorporate fire models,which project significant increases in forest area and biomass burned in the Northwest interior by 2100. Changes in other disturbances,such as wind,insects,and disease are also highly likely under climate change and biomass burned in the Northwest interior by 2100 (e.g., results from the MC1 model in Figure 19). The potential character of these disturbances under climate change is not yet adequately understood. Some likely effects have been suggested for individual disturbance processes,based on present disturbance patterns and tree-ring studies. For example, 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 more susceptible to attack by sap-sucking insects such as bark beetles. It is also possible that drought stress encourages attack by foliage eaters such as spruce budworm,although the evidence for this is divided. Some studies show attack by foliage eaters increasing when foliage is lush,others when it is stressed (Swetnam and Betancourt,1998; Thomson et al.,1984; Kemp et al.,1985;Swetnam and Lynch,1993;Larsson,1989;Price,1991). Very little is understood,however, about crucial questions of the interactions between multiple disturbances, e.g.,between insect attack and fire,under projected climate change and the changes in forest character that follow (Neilson et al.,1994). Finally, it is crucial to note that ecosystem models only project potential vegetation,the vegetation that would be present on a site in the absence of human intervention. In the Northwest, forest management and land-use change are presently, and are likely to remain,predominant factors shaping the structure,species mix, and extent of forest ecosystems (Franklin and Forman,1987). Interactions between these human-driven factors and the multiple direct and indirect pathways of climate influence on Northwest forests are essentially unexamined,and are key areas for research (Sohngen et al.,1998).

Adaptation Options

In contrast to water and salmon,where management already reflects at least limited awareness of climate variability, a survey of Northwest forest managers suggests they regard climate as unimportant,because mature stands are resilient to wide climatic ranges and because 40-70 year timber harvest rotations average out the effects of shorter-term climate variation (Mote et al.,1999b,Section 4.5,pp.73). Long-term climate trends are highly likely to make these assumptions invalid. Trees are likely to mature in a climate substantially different than when they were planted,possibly requiring changes to many dimensions of forest management even beyond those recently adopted due to endangered species concerns. Required adaptations might include:planting species best adapted to projected rather than present climate (e.g.,planting Douglas fir on suitable sites in the silver fir zone),or with known broad climatic resilience;further measures to restore and maintain complexity of forest structure and composition within intensively managed areas; managing forest density for reduced susceptibility to drought stress;and using precommercial thinning, prescribed burning,and other means to reduce the risk of large,high-intensity disturbances and to facilitate adaptation to changed climate regimes.

Managing forests effectively under these conditions is very likely to require increased capacity for long-term monitoring and planning. In addition,the importance of seasonal and interannual climate variability is highly likely to increase when forests are also stressed by long-term trends. Increased understanding of climate variability and predictive skill can allow projected periods of drought stress and fire risk to be factored into short-term forest-management decisions such as timing and species of planting,and use and timing of prescribed burning.

Maintaining forest ecosystem services and biological diversity is also likely to grow increasingly challenging under climate change. Options for doing so would include establishment of further protected areas,incorporating the maximum possible diversity of topography and landscape;active measures to promote species migration and maintain diversity, even in non-commercial forests;and further reduction in the intensity of commercial harvest.

4. Coasts

The Pacific Northwest has three distinct coasts. The inland marine waters of Puget Sound and the Strait of Juan de Fuca are bounded by narrow beaches backed by steep bluffs,and contain large areas of intensive shoreline development. The open Pacific coast has rocky bluffs and headlands punctuated by small pocket beaches,with wide beaches and sandspits in southern Washington and coastal sand dunes in central Oregon. This coast has generally low-intensity development,with no major cities and many stretches in parks,Indian reservations,and large undeveloped parcels,but contains a few pockets of increasing development. Finally, the coastal estuaries of Oregon and southern Washington are principally bordered by farmlands and small towns at river-mouths,and support extensive shellfish aquaculture and harvesting in their shallow waters and on their broad mudflats.

Present stresses in coastal regions include: bluff landsliding from heavy winter rains,principally on the steep hillsides around Puget Sound (Tubbs, 1974);erosion of beaches,barrier islands,sandspits and dunes on the open Pacific coast,principally due to winter storm waves;coastal flooding near river-mouths,particularly in areas that have neither upstream protection nor sufficient height above high tide;loss of wetlands to development or erosion;and invasion by exotic species,particularly in the coastal estuaries. Extensive development on coastal bluffs and near beaches,mainly in Puget Sound but increasingly also along the Pacific coast, has placed considerable valuable property at risk from erosion and landslides. Coastline near major river-mouths is sensitive both to ocean erosion and to variation in the rivers'sediment loads,which have increased on some rivers from adjacent clear-cutting,and decreased on others (including the Columbia) from damming (Canning,1991;Canning and Shipman,1994; Field and Hershman,1997; Park et al.,1993).

Little long-term data are available on coastal effects of climate variability, but a few effects are evident. Severe storm surges and erosion events on the open coast occur on average every five years. These appear to be associated with El Niño events,which increase erosion both by raising sea level for several months and by changing the direction of winds and waves from westerly to southwesterly (Komar and Enfield,1987). The 1997-1998 El Niño, for example, brought rapid erosion to a 1,000-foot built up segment of the sandspit on which Ocean Shores, Washington is situated, reversing several centuries of slow growth and requiring emergency construction of an armored beach fill. One Oregon study found that construction of shore protection measures follows an ENSO cycle,increasing sharply in the years immediately following a strong El Niño (Good,1994). As well as causing extreme erosion events,the elevated sea level during El Niño events also increases inundation risk in the low-lying areas of southern Puget Sound such as the city of Olympia,where it reaches 2-4 inches (5-10 cm). In contrast,La Niña events bring reduced erosion on the open coastline,but their heavier than normal winter rainfalls increase soil saturation and landsliding risk on coastal bluffs (Gerstel et al.,1997). For example,the four years with highest landslide incidence in the Seattle area were all La Niña winters (1933-4,1985-6,1996-7,1998-9).

Suggestive indications of a PDO signal in coastal phenomena have also been noted,although these remain speculative. For example,the warm decade of the 1980s, following the shift to warm-phase PDO in the late 1970s, was marked by two striking shifts in the ecosystem of Willapa Bay in southern Washington. The exotic cordgrass (Spartina), which was introduced to the bay nearly 100 years earlier, began a rapid expansion that threatened local species for the first time (Feist and Simenstad, 2000). After several productive decades, the condition of commercially important oysters in Willapa Bay also began a substantial decline in the late 1970s, though other factors such as pollution in the bay could also be responsible (Mote et al., 1999b, section 5.2, pp. 77-78).

Several coastal effects of future climate change have been identified, although detailed assessment of these remains to be done. Future climate warming is likely to raise mean sea level 10 to 35 inches in the 21st century, as opposed to the 4 to 8 inch rise of the 20th century. The apparent rise will differ from place to place, partly due to regional differences in ocean circulation and heat content — for example, the Hadley model projects a larger sea-level rise on the Pacific than the Atlantic coast of North America — and partly due to local variation in the rate of uplift or subsidence of the land surface. In the Pacific Northwest, regions of uplift are centered at the mouth of the Strait of Juan de Fuca, rising at 0.1 inch (2.5 mm) per year, and the mouth of the Columbia River, rising by 0.06 inch (1.7 mm) per year, while southern Puget Sound is subsiding at up to 0.08 inch (2 mm) per year (Shipman, 1989). Consequently, risks of sea-level rise are greatest in southern Puget Sound. Here, low-lying settlements are already at risk of inundation and existing shoreline protection is inadequate even for the high end of projected mean sea level rise, when the far greater risk is from mean rise combined with storm surge (Craig, 1993).

Higher mean sea level is also likely to increase sediment erosion and redistribution on the open coast, which possibly may be further amplified by projected shifts in prevailing wind direction to resemble sustained El Niño conditions. In addition, projected heavier winter rainfall is likely to increase soil saturation, landsliding, and winter flooding. All these changes would increase the risk to property and infrastructure on bluffs and beachfronts, and beside rivers. Climate change could also bring continued changes in coastal and estuarine ecosystems through changes in runoff and warmer water temperatures, with possible increased risk of exotic species introduction or health risks from shellfish contamination.

Adaptation Options

The most effective adaptation strategies for coastal climate impacts involve conserving remaining natural coastal areas and placing less property at risk in low-lying or flood-prone areas, on beaches, or on and below unstable slopes. Although these general adaptation strategies are well known, a series of interviews with coastal-zone managers about how they use climate information suggested that the coastal management system is not particularly adaptable even to current climate variability and its associated risks (Mote et al., 1999b, section 5.5, pp. 80-81). Most managers reported that they are seriously constrained in their ability to incorporate climate in planning, indeed that any climate considerations are overwhelmed in their planning by the present and potential endangered listings of various salmonid species. Many managers did not even view the long-range threat of flooding or inundation as a significant risk to the resources they managed. As for restricting development in vulnerable locations, there appears to be little inclination to move in that direction. A weaker and perhaps more feasible alternative would be to assign more of the risk of living in a coastal zone to property-owners, through incorporating geological assessment into property-insurance rates.

ADDITIONAL ISSUE

Agriculture

Due to limited time and resources in this first Assessment, the Northwest regional study was restricted to the four critical issues discussed above. The choice of these four reflected the concerns of stakeholders in the regional workshops, but was emphatically not intended to imply that these are the only important areas of impact in the Northwest. Other areas of potentially significant impact not covered in this Assessment might include, for example, human health, urban quality of life, recreation, and agriculture. Agriculture, because of its importance in many parts of the region, is a particularly conspicuous omission, and an obvious priority for subsequent assessment. A very preliminary discussion is provided here, based on work conducted by the agriculture sector team of the National Assessment.

The Agriculture Sector Assessment included modeling of climatic effects on several crops at five locations in the Northwest: Boise, Idaho; Medford and Pendleton, Oregon; and Yakima and Spokane, Washington. The studies examined dryland and irrigated yields, and water use for irrigation, under several climate scenarios and using several crop models. Under all scenarios, dryland yields for most crops were projected to increase through the 21st century. The exception was potatoes, whose dryland yields by 2090 declined by as much as 30-35%, with the largest declines in Idaho. Changes in irrigated yields and irrigation water requirements were more mixed. Wheat and potatoes showed large reductions in irrigated yields (7-25% and 35-40%, respectively by 2090), while hay increased 50-70% and tomatoes showed a mixed trend, increasing 15-20% by 2030, then declining to roughly present yields by 2090. Irrigation water needs declined by 20-40% for wheat, and increased by 10-40% for hay, potatoes and tomatoes. To the extent that aggregate irrigation water needs increase under the combined effects of climate change, CO_2 enrichment, and agricultural response, this would exacerbate the summer water shortages and allocation conflicts discussed above. Interactions between climate and related impacts on agriculture and forest lands, and linkages between them as mediated by human land-use conversion and management, are little understood and remain important knowledge needs (Alig et al., 1998).

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Although this Assessment has produced and synthesized significant advances in our understanding of climate impacts in the four key areas examined in detail, clear needs for additional knowledge are evident for each of them, in order to understand impacts and vulnerabilities more thoroughly and assess potential responses.

For freshwater, the analysis here has concentrated primarily on the response of the Columbia River system to climate variability and change, and on the consequences of projected summer shortages on the reliability with which various present management objectives could be met under potential future flow regimes. Further analysis is required to: project future shifts in demand for multiple uses, and to examine the joint effects of climate variability and change on seasonal supply and demand; to identify the degree of vulnerability to scarcity, assess the effects of alternative operational rules and allocation schemes, and identify and evaluate specific response options. In addition, this Assessment has made only preliminary investigation of other basins than the Columbia. In particular, further examination is needed to characterize the effects of future climate variability and change on winter flooding risk in the low-elevation rainfed and mixed basins west of the Cascades. In view of the rapid development of west-side metropolitan areas, assessment of these climate risks, of how alternative future development patterns may compound or mitigate it, and of potential responses, are of high priority.

For salmon, research priorities include further characterization of historical climate influences on salmon and identification of the mechanisms by which they operate. In particular, very little is known of the effect of climate variability and change on the open-ocean phase of salmon's life cycle. For forests, the top priority is further work on the effects of climate and atmospheric CO_2 on Northwest forests' water use efficiency, which is necessary to understand even the direction of future climate effects on forests. Other priorities include interactions between climate and forest disturbances, including fire, insects, and disease, as well as interactions between these disturbances. Finally, little work has been done quantifying the effects of climate variability on the region's coasts.

Assessment of other sectors and issues than the four examined in detail here will be required. Particularly important areas for investigation in subsequent Northwest climate assessments will be agriculture, energy, and urban issues (e.g., infrastructure, hazards, and quality of life).

More broadly, there are several areas of climate research that are important for better understanding Northwest impacts. This assessment has been based on a single run each of two primary climate models, each using the same emissions scenario, with some additional results drawn from single runs of other models. A more reliable regional assessment would require controlled regional-level comparison of several state-of-the-art models, each with a statistical ensemble of multiple similar runs under each of several emissions scenarios. Ensembles of multiple runs for each model are necessary to allow examination of patterns of climate variability projected by each model. For example, several results in this assessment were strongly influenced by the fact that in the particular Hadley model run employed, the 2020s were an unusually wet decade. Studies of such variability over ensembles of multiple model runs are necessary to interpret such excursions. Comparisons of multiple models with several emission scenarios would allow useful model comparison and explanation of significant regional-scale disparities, and examination of how major impacts vary with higher or lower future emissions.

Understanding the dynamics of longer-term variability, in particular whether and how presently observed patterns would shift under a global greenhouse trend, requires further development of climate models. Models are now beginning to represent ENSO, but cannot yet reproduce interdecadal variability of the size and character observed, either in the PDO or elsewhere in the world.

More accurate fine-scale modeling of climate-topography interactions in the Northwest is also required, and their effects on the region's rivers, estuaries and coasts, to understand several processes that strongly affect multiple areas of regional impacts. These processes include, for example, coastal upwelling, the interaction of fresh and salt water in estuaries, windstorms, and rain-on-snow events.

Because interannual and interdecadal climate variability exert such strong influences on the Northwest, better understanding of their dynamics and their relationship to long-term climate trends is also required. Their effects on summer climate are potentially important and have been little studied. An immediate uncertainty is whether the PDO has recently re-entered its cool phase, and indeed, whether the PDO will continue to exhibit more or less regular phase changes. If the PDO continues to behave for the next few decades as it has over the 20th century, and it has re-entered a cool phase, the resultant cooler wetter regional climate would be likely to partly offset greenhouse warming over the next two or three decades, until the PDO reverses again. While this could delay the onset of significant impacts from climate change, it could also obscure the need to undertake long-lead adaptation measures when they can be done with the least disruption.

Finally, a large but crucial area for further research concerns interactions between climate changes, the ecological and hydrological impacts discussed here, and human responses. Land-use change has been the dominant source of environmental stresses in the Northwest over the 20th century, and further population and economic growth are highly likely to bring more pressure for conversion, with complex interactions between metropolitan development, forestry, and other land uses. Coherent scenarios of socioeconomic futures in the Northwest that elaborate more climate-relevant aspects, especially land use and development, are needed. So are methods to couple socioeconomic projections to climatic, ecological, and hydrological models to allow more precise examination of impacts and potential responses. These methods should permit the examination of alternative sets of technological and institutional assumptions, and should support comprehensive examination of uncertainties across socioeconomic, climatic, and ecological domains.

Furthermore, more insight is needed into the feasibility and likely consequences of various adaptation strategies, addressing sectors both singly and jointly. This Assessment has made only a preliminary identification of potential adaptation measures for each sector, and has not attempted to assess their costs, benefits, efficacy, or ancillary effects. Systematic examination of technological, managerial, and institutional adaptation options should be conducted, based on partnerships between researchers, stakeholders, and experienced resource managers. Such partnership will be necessary to identify, develop, and assess adaptation options that are effective, low in cost, and are practical to implement in the context of present management practices, which strongly shape climate impacts. For example, future forest-management and agricultural practices are very likely to strongly mediate climate effects on these sectors, and may also contribute to mitigation of climate change through adjustments to management that increase sequestration of carbon in forests and soils. Where the present assessment has identified that climate variability and change are inadequately considered even in long-lived investment, resource management and infrastructure design decisions, research is needed to identify the cause and potential approaches to increase the time-horizon of planning. Two aspects of adaptation will be particularly important: investigation of interactions with impacts and responses in Canada, since many of the affected resources are shared; and linkages, whether conflicting or complementary, between adaptation measures in multiple sectors. For example, increasing water storage to manage increased summer drought suggests maintaining present dams or building more, while restoring salmon habitat to reduce their vulnerability to climate change would suggest the opposite. The most useful approach to assessment would examine impacts and adaptation measures together with emission scenarios and mitigation measures, to identify the most cost-effective strategy for dealing with climate-change in aggregate.

LITERATURE CITED

Agee, J. K., *Fire Ecology of Pacific Northwest Forests*, Island Press, Washington, DC, 1993.

Alig, R. J., D. M. Adams, B. A. McCarl, Impacts of incorporating land exchanges between forestry and agriculture in sector models, *Journal of Agricultural and Applied Economics*, *30*, 2 (December), 389-401, 1998.

Bachelet, D., M. Brugnack, and R. P. Neilson, Sensitivity of a biogeography model to soil properties, *Ecological Modeling*, *109*, 77-98, 1998.

Bachelet, D., R. P. Neilson, J. M. Lenihan, and R. J. Drapek, Climate change effects on vegetation distribution and carbon budget in the US, *Ecosystems*, in review, 2000.

Baker, P. F., T. P. Speed, and F. K. Ligon, Estimating the influence of temperature on the survival of chinook salmon smolts migrating through the Sacramento San Joaquin River delta of California, *Canadian Journal of Fisheries and Aquatic Sciences*, *52*, 855-863, 1995.

Baker, W. L., Long-term response of disturbance landscapes to human intervention and global change, *Landscape Ecology*, *10*, 143-159, 1989.

Bazzaz, F. A., S. L. Bassow, G. M. Berntson, and S. C. Thomas, Elevated CO_2 and terrestrial vegetation: Implications for and beyond the global carbon budget, in *Global Change and Terrestrial Ecosystems*, edited by B. Walker and W. Steffen, pp. 43-76, Cambridge University Press, New York, NY, 1996.

Beamish, R. J., and D. R. Bouillon, Pacific salmon production trends in relation to climate, *Canadian Journal of Fisheries and Aquatic Sciences*, *50*, 1002-1016, 1993.

Beechie, T., E. Beamer, and L. Wasserman, Estimating Coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration, *North American Journal of Fisheries Management*, *14*, 797-811, 1994.

Bisbal, G. A., and W. E. McConnaha, Consideration of ocean conditions in the management of salmon, *Canadian Journal of Fisheries and Aquatic Sciences*, *55*, 2178-2186, 1998.

Boer, G. J., N. A. McFarlane, R. Laprise, J. D. Henderson, and J.-P. Blanchet, The Canadian Climate Centre spectral atmospheric General Circulation Model, *Atmosphere-Ocean*, *22*(4), 397-429, 1984.

Boer, G. J., G. M. Flato, M. C. Reader, and D. Ramsden, A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: Experimental design and comparison with the instrumental record for the 20th century, *Climate Dynamics*, *16*, 405-426, 1999a.

Boer, G. J., G. M. Flato, and D. Ramsden, A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: projected climate for the 21st century, *Climate Dynamics*, *16*, 427-450, 1999b.

Bottom, D. L., Restoring salmon ecosystems: Myth and reality, *Restoration and Management Notes*, *13*, 162-170, 1995.

Brubaker, L. B., Responses of tree populations to climatic change, *Vegetation*, *67*, 119, 1986.

Bury, R. B., Vertebrates in the Pacific Northwest: Species richness, endemism, and dependency on old-growth forests, in *Biological Diversity: Problems and Challenges*, edited by S. K. Majumdar, F. J. Brenner, J. E. Lovich, J. F. Schalles, and E. W. Miller, pp. 392-404, Pennsylvania Academy of Science, Easton, Pennsylvania, 1994.

Callahan, B., E. Miles, and D. Fluharty. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sciences* *32*:269-293, 1999.

Canning, D. J., Sea level rise in Washington State: State-of-the-knowledge, impacts, and potential policy issues, Washington Department of Ecology, Olympia, Washington, 1991.

Canning, D. J., and H. Shipman, Coastal erosion management studies in Puget Sound, Washington: Volume 1, executive summary, report 94-94, Washington Department of Ecology, Olympia, Washington, 1994.

Carter, M. F., and K. Barker, An interactive database for setting conservation priorities for western neotropical migrants, in *Status and Management of Neotropical Migratory Birds*, edited by D. M. Finch and P. W. Stangel, *US Forest Service General Technical Report RM-GTR-229*, pp. 120-144, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado, 1993.

Cohen, S. J., K. A. Miller, A. F. Hamlet, and W. Avis, Climate change and resource management in the Columbia River Basin, *Water International*, in press, 2000.

Craig, D., Preliminary assessment of sea level rise in Olympia, Washington: Technical and policy implications, City of Olympia Public Works Department Policy and Program Development Division, Olympia, Washington, 1993.

Dale, V. H., and J. F. Franklin, Potential effects of climate change on stand development in the Pacific Northwest, *Canadian Journal of Forest Resources, 19*, 1581, 1989.

Daly C, D. Bachelet J. M. Lenihan, R. P. Neilson, W. Parton and D. Ojima, Dynamic simulation of tree-grass interactions for global change studies, *Ecological Applications, 10*(2), 449-469, 2000

dell'Arciprete, P., N. Mantua, and R.C. Francis, The instrumental record of climate variability in the Pacific Northwest, Progress report for Year 1, JISAO Climate Impacts Group, University of Washington, Seattle, Washington, 1996.

dell'Arciprete, P., D. L. Peterson, R.C. Francis, and N. Mantua, Climate reconstruction through tree growth indices, unpublished manuscript, available from the University of Washington Climate Impacts Group, Seattle, Washington, 1998.

Detling, L.E., Relic islands of xeric flora west of the Cascade Mountains in Oregon, *Madrono, 12*, 39-47, 1953.

Detling, L.E., Historical background of the flora of the Pacific Northwest, *Bulletin No. 13*, Museum of Natural History, University of Oregon, Eugene, Oregon, 1968..

Ellsworth, D. S., CO_2 enrichment in a maturing pine forest: Are CO_2 exchange and water status in the canopy affected?, *Plant, Cell, and Environment, 22*, 461-472, 1999

Emmett, R.L., and M.H. Schiewe (Eds.), Estuarine and ocean survival of Northeast Pacific salmon: Proceedings of the workshop, US Department of Commerce, NOAA Technical Memo., NMFS-NWFSC-29, 1997.

Emmett, R.L., and R. D. Brodeur, Recent changes in the pelagic nekton community off Oregon and Washington in relation to some physical oceanographic conditions, North Pacific Anadromous Fish Commission, Bull. No. 2, in press, 2000.

Feist, B.E., and C.A. Simenstad, Expansion rates and recruitment frequency of exotic smooth cordgrass, (Spartina alterniflora) (Loisel) colonizing unvegetated littoral flats in Willapa Bay, Washington, *Estuaries, 23*(2), 268-275, 2000.

FEMAT (Forest Ecosystem Management Assessment Team), Forest ecosystem management: An ecological, economic, and social assessment, US Department of the Interior, US Department of Agriculture, US Department of Commerce, and US Environmental Protection Agency, Washington, DC, 729 pp., 1993.

Field, J., and M. Hershman, Assessing coastal zone sensitivity and vulnerability to regional climate variability and change in the Pacific Northwest, Climate Impacts Group, University of Washington, Seattle, Washington, 1997.

Flato, G. M., G. J. Boer, W. G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A. J. Weaver, The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate, *Climate Dynamics*, in press, 2000.

Fosberg, M.A., L. O. Mearns, and C. Price, Climate change: Fire interactions at the global scale: Predictions and limitations of methods, in *Fire in the Environment*, edited by P. J. Crutzen and J. G. Goldammer, Wiley and Sons, New York, 1992.

Francis, R.C., Sustainable use of salmon: Its effects on biodiversity and ecosystem function, in *Harvesting Wild Species —- Implications for Biodiversity Conservation*, edited by C.H. Freeze, pp. 626-670, Johns Hopkins University Press, Baltimore, Maryland, 1997.

Francis, R.C., S.R. Hare, A.B. Hollowed, and W. S. Wooster, Effects of interdecadal climate variability on the oceanic ecosystems of the Northeast Pacific, *Fisheries Oceanography, 7*, 1-21, 1998.

Franklin, J. F., Pacific Northwest forests, in *North American Terrestrial Vegetation*, edited by M. G. Barbour and W. D. Billings, pp. 103-130, Cambridge University Press, Cambridge, United Kingdom, 1988.

Franklin, J. F., and C. T. Dyrness, *Natural Vegetation of Oregon and Washington*, Oregon State University Press, Corvallis, Oregon, 1973.

Franklin, J. F., and R.T.T. Forman, Creating landscape patterns by forest cutting: Ecological consequences and principles, *Landscape Ecology*, 1, 5-18, 1987.

Franklin, J. F., W. H. Moir, G.W. Douglas, and C. Wiberg, Invasion of subalpine meadows by trees in the Cascade Range, *Arctic and Alpine Research, 3*, 215-224, 1971.

Franklin, J. F., et al., Effects of global climatic change on forests in northwestern North America, *Northwest Environmental Journal*, 7, 233-254, 1991.

Gardner, R.H., W.W. Hargrove, M. G. Turner, and W. H. Romme, Climate change, disturbances, and landscape dynamics, in *Global Change and Terrestrial Ecosystems*, edited by B. Walker and W. Steffen, pp., 149-172, Cambridge University Press, Cambridge, United Kingdom, 1996.

Gerstel, W. J., M. J. Brunengo, W. S. Lingley, Jr., R.L. Logan, H. Shipman, and T. J. Walsh, Puget Sound bluffs: The where, why, and when of landslides following the holiday 1996-97 storms, *Washington Geology, 25*(1), 17-31, 1997.

Gholz, H.L., Environmental limits on aboveground net primary production, leaf area, and biomass in vegetation zones of the Pacific Northwest, *Ecology, 63,* 469, 1982.

Giorgi, F., and G. Bates, On climatological skill of a regional model over complex terrain, *Monthly Weather Review, 117,* 2325-2347, 1989.

Giorgi, F., C.S. Brodeur, and G.T. Bates, Regional climate change scenarios over the United States produced with a nested regional climate model, *Journal of Climate, 7,* 375-399, 1994.

Glantz, M.H., Consequences and responsibilities in drought forecasting: The case of Yakima, 1977, *Water Resources Research, 18,(*1), pp. 3-13, 1982.

Good, J.W., Shore protection policy and practices in Oregon: An evaluation of implementation successes, *Coastal Management, 22,* 325-352, 1994.

Graumlich, L. J., Precipitation variation in the Pacific Northwest (1675-1975) as reconstructed from tree rings, *Annals of the Association of American Geographers, 77,* 19-29, 1987.

Graumlich, L. J., Subalpine tree growth, climate, and increasing CO_2: An assessment of recent growth trends, *Ecology, 72,* 1-11, 1991.

Gray, K. N., The impacts of drought on Yakima Valley irrigated agriculture and Seattle municipal and industrial water supply, master's thesis, School of Marine Affairs, University of Washington, Seattle, Washington, 1999.

Grier, C.C., and S. Running, Leaf area of mature northwestern coniferous forests: Relation to site water balance, *Ecology, 58,* 893, 1977.

Hamlet, A. F., and D. P. Lettenmaier, Effects of climate change on hydrology and water resources objectives in the Columbia River Basin, *Journal of American Water Resources Association, 35*(6), 1597-1623, 1999.

Hare, S. J., N. J. Mantua, and R.C. Francis, Inverse production regimes: Alaskan and West Coast Pacific salmon, *Fisheries, 24,* 6-14, 1999.

Harmon, M.E., W. K. Ferrell, and J. F. Franklin, Effects on carbon storage of converting old-growth forests to young forests, *Science, 247,* 699-702, 1990.

Hargreaves, B. N., Early ocean survival of salmon off British Columbia and impacts of the 1983 and 1991-1995 El Niño events, in *Estuarine and Ocean Survival of Northeast Pacific Salmon: Proceedings of the Workshop*, edited by R.L. Emmett and M.H. Schiewe, pp., 197-211, NOAA Tech. Memo., NMFS-NWFSC-29, Seattle, Washington, 1997.

Harr, R. D., Water flux in soil and subsoil in a steep forested slope, *Journal of Hydrology, 33,* 37-58, 1977.

Haynes, R. W., D. M. Adams, and J. R. Mills, The 1993 RPA Timber Assessment update, USDA Forest Service, Rocky Mountain Forest and Range Experimental Station, *General Technical Report RM-GTR.* March 1995.

Henjum, M. G., J. B. Karr, D. L. Bottom, D. Perry, J. C. Bednarz, S. G. Wright, S.A. Beckwitt, and E. Beckwitt, Interim protection for late-successional forests, fisheries, and watersheds: National forests east of the Cascade crest, Oregon, and Washington, *The Wildlife Society Technical Review 94-2,* Bethesda, Maryland, 245 pp., 1994.

Heyerdahl, E.K., Spatial and temporal variation in historical fire regimes of the Blue Mountains, Oregon, and Washington: The influence of climate, Ph.D. dissertation, College of Forest Resources, University of Washington, Seattle, Washington, 1997.

Huffaker, R., N. K. Whittlesey, and P. R. Wandschneider, Institutional feasibility of contingent water marketing to increase migratory flows for salmon on the Upper Snake River, *Natural Resources Journal, 33,* 671-696, Summer 1993.

Hulme, M., E.M. Barrow, N.W. Arnell, P.A. Harrison, T. C. Johns, and T. E. Downing, Relative impacts of human-induced climate change and natural variability, *Nature, 397,* 688-691, 1999.

Jackson, P. L.,and A. J. Kimmerling,(Eds.), *Atlas of the Pacific Northwest, 8th edition*, Oregon State University Press,Corvallis,Oregon,1993.

Johns T. C.,R.E.Carnell, J. F. Crossley, J. M.Gregory, J. F. B. Mitchell,C.A.Senior, S. F. B. Tett,and R.A.Wood,The Second Hadley Centre coupled ocean-atmosphere GCM: Model description,spinup,and validation, *Climate Dynamics, 13*, 103-134,1997.

Jones, J.A.,and G. E.Grant, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades,Oregon, *Water Resources Research, 32*, 959-974,1996.

Jones, J. A.,and G. E.Grant,Hydrologic processes and peak discharge response to forest harvest, regrowth, and roads in ten small experimental basins, western Cascades,Oregon, *Water Resources Research*, in review, 2000.

Keane,R.E.,and S. F. Arno,Rapid decline of whitebark pine in western Montana: Evidence from 20-year remeasurements, *Western Journal of Applied Forestry, 8*(2),44-47,1993.

Kellogg,E.,(Ed.),Coastal temperate rain forests: Ecological characteristics,status,and distribution worldwide, *Ecotrust Occasional Paper Series 1*, Ecotrust and Conservation International, Portland, Oregon,and Washington,DC,64 pp.,1992.

Kemp, W. P., D. O. Everson,and W. G. Wellington, Regional climatic patterns and western spruce budworm outbreaks,USDA Forest Service Cooperative State Research Service, *Technical Bulletin Number 1693*, USDA,Corvallis,Oregon,1985.

Kendall,K.C.,Whitebark Pine: Ecosystem in peril, in *Our living resources: A report to the Nation on the distribution, abundance, and health of US plants, animals, and ecosystems*, edited by E. T. LaRoe, G. S. Farris,C.E.Puckett, P. D. Doran,M .J. Mac,pp.228-230, US National Biological Service, Washington,DC,1995.

Klahn, J.,This time,city folks will bear cost of restoring species,(AP), *Seattle Times*, pg.1,September 5,1999.

Komar, P. D.,and D. B.Enfield,Short-term sea-level changes and coastal erosion,in *Sea-level Fluctuations and Coastal Evolution, Special Publication 41*, edited by D. Nummedal, O. Pilkey, and J. D. Howard,pp.17-27, Society of Economic Paleontologists and Mineralologists,1987.

Laprise,R., D. Caya,M.Giguere, G. Bergeron,H.Cote, J.-P. Blanchet, G. J. Boer, and N.A.McFarlane,Climate and climate change in western Canada as simulated by the Canadian Regional Climate Model, *Atmosphere-Ocean, 36*, 119-167,1998.

Larsson,S.,Stressful times for the plant stress-insect performance hypothesis, *Oikos, 56*, 277-283,1989.

Law, B.E.,R.H. Waring, P. M.Anthoni,and J. D.Abers, Measurements of gross and net ecosystem productivity and water vapor exchange of a Pinus ponderosa ecosystem,and an evaluation of two generalized models, *Global Change Biology, 5*, 1-15,1999.

Lehmkuhl, J. F., P. F. Hessburg,R.L.Everett,M.H.Huff, and R. D. Ottmar, Historical and current forest landscapes of eastern Oregon and Washington, Part 1: Vegetation pattern and insect and disease hazards, *General Technical Report PNW-GTR-328*, USDA Forest Service,Corvallis,Oregon,1994.

Leung,L.R.,and S. J. Ghan, Pacific Northwest climate sensitivity simulated by a regional climate model driven by a GCM. Part I: Control simulations, *Journal of Climate, 12*(7),2010-2030,1999a.

Leung,L.R.,and S. J. Ghan, Pacific Northwest climate sensitivity simulated by a regional climate model driven by a GCM. Part II: 2 times CO_2 simulations, *Journal of Climate, 12*(7),2031-2053,1999b.

Little,R.L., D. L. Peterson,and L.L.Conquest, Regeneration of subalpine fir (*Abies lasiocarpa*) following fire: Effects of climate and other factors, *Canadian Journal of Forest Research, 24*, 934-944, 1994.

Mac,M. J., P.A.Opler, C.E.Puckett Haecker, and P. D. Doran (Eds.),Status and trends of the Nation's biological resources, *US Geological Survey*, US Department of the Interior, Biological Resources Division,Reston, Virginia,1998.

Mantua, N. J.,S.R.Hare, Y. Zhang, J. M.Wallace,and R.C. Francis,A Pacific interdecadal climate oscillation with impacts on salmon production, *Bulletin of the American Meteorological Society, 78*, 1069—1079, 1997.

Mantua, N. J., P. dell'Arciprete,and R.C. Francis, Patterns of climate variability in the Pacific Northwest: A regional 20th century perspective,in Impacts of climate variability and climate change in the Pacific Northwest: An integrated assessment,edited by E.L. Miles,Climate Impacts Group,University of Washington,Seattle, Washington,1999.

Marcot,B. G.,R.S.Holthausen, J.Teply, and W. D. Carrier, Old-growth inventories: Status,definitions,and visions for the future,in *Wildlife and Vegetation in Unmanaged Douglas-Fir Forests*, edited by L. F. Ruggiero,K. Aubry, and M.H.Huff, *US Forest Service General Technical Report PNW-GTR-285*, pp.47-60, Pacific Northwest Research Station, Portland,Oregon, 1991.

Mason,R.R.,and B.E.Wickman,The Douglas-fir tussock moth in the interior Pacific Northwest, chapter 10,in *Dynamics of Forest Insect Populations*, edited by A.A. Berryman,Plenum Press,New York,1988

Matthews, D.A.,and T. Hovland,Nested model simulations of regional orographic precipitation,Global Climate Change Response Program Report,Bureau of Reclamation,Denver, Colorado, 61 pp.,1997.

McCullough, D.A.,A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids,with special reference to Chinook Salmon,EPA Region 10 Report 910-R-99-010, July 1999.

McFarlane, N.A., G. J. Boer, J. P. Blanchet,and M.Lazare, The Canadian Climate Centre second-generation general circulation model and its equilibrium climate, *Journal of Climate, 5*, 1013-1044,1992.

McKenzie, D., D. L. Peterson,and E.Alvarado,Predicting the effect of fire on large-scale vegetation patterns in North America, USDA Forest Service Research Paper PNW-489, Fort Collins,Colorado,1996.

Miles,E.L.,A.Hamlet,A.K.Snover, B.Callahan,and D. Fluharty. 2000. Pacific Northwest regional assessment: The impacts of climate variability and climate change on the water resources of the Columbia River Basin. *Journal of American Water Resources Association, 36*(2):399-420,2000.

Miller, A. J., D. R.Cayan, T. P. Barnett, N. E.Graham,and J. M.Oberhuber,The 1976-1977 climate shift in the Pacific Ocean, *Oceanography*, *7*, 21-26,1994.

Miller, A. J., D. R.Cayan,and W. B.White,A westward-intensified decadal change in the North Pacific thermocline and gyre-scale circulation, *Journal of Climate, 11*, 3112-3127,1998.

Miller, K.A., Water banking to manage supply variability, in *Advances in the Economics of Environmental Resources*, vol.1.,edited by D. C.Hall,pp.185-210, JAI Press,Greenwich,Connecticut,1996.

Miller, K.A.,S.L.Rhodes,L. J. MacDonnell, Water allocation in a changing climate: Institutions and adaptation, *Climatic Change, 35*,157-177,1997.

Miller, R. F.,and J.A.Rose, Western juniper expansion in eastern Oregon, *Great Basin Naturalist, 55*, 37-45, 1995.

Miller, R. F.,and P. E.Wigand,Holocene changes in semi-arid pinyon-juniper woodlands, *BioScience, 44(7)*, 465-474,1994.

Mitchell J. F. B.,T. C. Johns, J. M.Gregory, and S. Tett, Climate response to increasing levels of greenhouse gases and sulphate aerosols, *Nature, 376*, 501-504, 1995.

Mitchell J. F. B.,and T. C. Johns,On modification of global warming by sulfate aerosols, *Journal of Climate, 10*(2),245-267,1997.

Mooney, H.A., J. Canadell, F. S.Chapin,III, J. R. Ehleringer, C.H.. Korner, R.E. McMurtrie, W. J. Parton,L. F. Pitelka,and E.-D. Schulze,Ecosystem physiology responses to global change,in, *The Terrestrial Biosphere and Global Change: Implications for Managed and Unmanaged Ecosystems*, edited by B. Walker, W. Steffen, J. Canadell,and J. Ingram,pp.141-189, Cambridge University Press,Cambridge,UK,1999.

Morse,L.E., J.T. Kartesz,and L.S. Kutner, Native vascular plants,in Our living resources: A report to the Nation on the distribution, abundance,and health of US plants, animals,and ecosystems,edited by E.T. LaRoe, G. S. Farris,C.E.Puckett, P. D. Doran,M. J. Mac,US National Biological Service, Washington,DC,1995.

Mote, P.W.,W. S. Keeton,and J. F. Franklin,Decadal variations in forest fire activity in the Pacific Northwest, 11th Conference on Applied Climatology,American Meteorological Society, Boston,Massachusetts,1999a.

Mote, P.W.,et al.,Impacts of climate variability and change: Pacific Northwest,A report of the Pacific Northwest Regional Assessment Group for the US Global Change Research Program,Climate Impacts Group,University of Washington,Seattle, Washington, November 1999b.

Myers, J. M.,et al.,Status review of chinook salmon from Washington,Idaho,Oregon,and California,NOAA Tech.Memo.NMFS-NWFSC-35,1998.

National Marine Fisheries Service (NMFS),Northwest Region,West Coast Salmon and the Endangered Species Act,(http://www.nwr.noaa.gov/1salmon/salmesa/index.htm),2000.

Neilson,R. P., G.A.King,and J. Lenihan,Modeling forest response to climatic change: The potential for large emissions of carbon from dying forests,in *Carbon Balance of the World's Forested Ecosystems: Towards a Global Assessment*, edited by J. Kanninen,pp.150-162, Academy of Finland, Joensuu, Finland,1994.

Neilson,R. P.,and R. J. Drapek, Potentially complex biosphere responses to transient global warming, *Global Change Biology, 4*, 101-117,1998.

Neilson R. P.,I.C.Prentice,B.Smith,T. G. F. Kittel,and D. Viner, Simulated changes in vegetation distribution under global warming,in *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, edited by R.T.Watson,M.C.Zinyowera,R.H.Moss,and D. J. Dokken,pp.439-456,Cambridge University Press, Cambridge,United Kingdom,1998.

National Research Council, *Upstream*, National Academy Press,Washington,DC,1996.

Nijssen,B., D. P. Lettenmaier, X.Liang,S. W.Wetzel,and E. F.Wood,Streamflow simulation for continental-scale river basins, *Journal of Water Resources Research*, 33, 4,pp 711ff, 1997.

Noss,R. F.,E.T. LaRoe,III,and J. M.Scott,Endangered ecosystems of the United States: A preliminary assessment of loss and degradation, *National Biological Service Biological Report 28,* Washington,DC,58 pp., 1995.

Overpeck,J.T., D. Rind,and R.Goldberg,Climate-induced changes in forest disturbance and vegetation, *Nature, 343*, 51-53,1990.

Park,R.A., J. K.Lee,and D. J. Canning, Potential effects of sea-level rise on Puget Sound wetlands, *Geocarto International,* 99-110,1993.

Parsons, G. L., G. Cassis,A.R.Moldenke, J. D. Lattin, N. H. Anderson, J. C.Miller, P. Hammond,and T. D. Schowalter, Invertebrates of the H. J.Andrews experimental forest, western Cascade Range,Oregon, Part V: An annotated list of insects and other arthropods, *US Forest Service General Technical Report PNW-GTR-290*, Pacific Northwest Research Station, Portland,Oregon,168 pp., 1991.

Pearcy,W. G., *Ocean Ecology of North Pacific Salmonids*, University of Washington Press,Seattle, Washington,1992.

Pearcy,W. G.,K. Y.Aydin,and R. D. Brodeur,What is the carrying capacity of the North Pacific Ocean for salmonids?, *Pisces Press*, *7*, 2,17-22,1999.

Perkins,R.,Climatic and physiographic controls on peak-flow generation in the western Cascades,Oregon, Ph.D. dissertation,Oregon State University, Corvallis,Oregon, 1997.

Peterson, D. L.,Climate,limiting factors and environmental change in high-altitude forests of western North America,in *Climatic Variability and Extremes: The Impact on Forests*, edited by M.Benistion and J. L.Innes, Springer-Verlag,Heidelberg,Germany, 1998.

Peterson, D.W.,and D. L. Peterson,Growth responses of mountain hemlock (Tsuga mertensiana) to interannual and interdecadal climate variability, *Ecology*, in review, 2000.

Pinnix, W.,Climate and Puget Sound,in JISAO/SMA Year 3 report,Climate Impacts Group,University of Washington, Seattle, Washington,1998.

Price, P.W.,The plant vigor hypothesis and herbivore attack, *Oikos, 62*, 244-251,1991.

Quigley, R. W.,R. W. Haynes,and R.T.Graham,Integrated scientific assessment for ecosystem management in the interior Columbia Basin, *USDA Forest Service General Technical Report PNW-382*, USDA Forest Service, Corvallis,Oregon,1996.

Quinn,T. P.,and D. J. Adams,Environmental changes affecting the migratory timing of American shad and sockeye salmon, *Ecology*, *77*, 1151-1162,1996.

Reeves, G. H., F. H.Everest,and T. E.Nickelson, Identification of physical habitats limiting the production of Coho salmon in western Oregon and Washington, *USDA Forest Service General Technical Report PNW-245*, US Forest Service,Corvallis,Oregon,1989.

Rochefort,R.M.,R. L.Little,A. Woodward, D. L. Peterson, Changes in subalpine tree distribution in western North America: A review of climate and other factors, *The Holocene*, *4*, 89-100,1994.

Ryan,K.C., Vegetation and wildland fire: Implications of global climate change, *Environment International*, *17*, 169-178,1991.

Shipman, H., Vertical land movements in coastal Washington: Implications for relative sea level changes, Washington Department of Ecology, Olympia, Washington, 1989.

Sohngen, B., R. Mendelsohn, and R. Neilson, Predicting CO_2 emissions from forests during climatic change: A comparison of natural and human response models, *Ambio*, *27*, 509-513, 1988.

Swetnam, T. W., and J. L. Betancourt, Fire-Southern Oscillation relations in the southwestern United States, *Science, 249*, 1017-1020, 1990.

Swetnam, T. W., and J. L. Betancourt, Meso-scale disturbance and ecological response to decadal climate variability in the American southwest, *Journal of Climate*, *11*, 3218-3247, 1998.

Swetnam, T. W., and A. M. Lynch, Multicentury regional-scale patterns of western spruce budworm outbreaks, *Ecological Monographs*, *63*, 399-422, 1993.

Terleckyj, N. E., Analytic documentation of three alternate socioeconomic projections, 1997—2050, NPA Data Services, Washington, DC, 1999a.

Terleckyj, N. E., Development of three alternate national projections scenarios, 1997—2050, NPA Data Services, Washington, DC, 1999b.

Tett, S. B., P. A. Stott, M. R. Allen, W. J. Ingram, and J. F. B. Mitchell, Causes of twentieth century temperature change, *Nature*, *399*, 569-572, 1999.

Thomson, A. R., R. F. Sheperd, J. W. E. Harris, and R. J. Silversides, Relating weather to outbreaks of western spruce budworm in British Columbia, *Canadian Entomologist*, *116*, 375-381, 1984.

Torn, M. S., and Fried, J. S., Predicting the impacts of global warming on wildland fire, *Climate Change, 21*, 257-274, 1992.

Trenberth, K. E., The definition of El Niño, *Bulletin of the American Meteorological Society*, *78*, 2771-2777, 1997.

Tubbs, D. W., Landslides in Seattle, Washington Division of Geology and Earth Resources Information Circular 52, Washington Department of Natural Resources, Olympia, Washington, 1974.

US Census Bureau, Historical state population series, 2000, at: http://www.census.gov/population/www/estimates/st_stts.html

US Department of Agriculture, Economic Research Service, US State Fact Sheets, 2000 (http://www.ers.usda.gov/epubs/other/usfact/), 2000.

VEMAP Members, Vegetation/ecosystem modeling and analysis project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling, *Global Biogeochemical Cycles*, *4*, 407-437 1995.

Walker, R. V, K. W. Myers, N. D. Davis, K. Y. Aydin, K. D. Friddland, H. R. Carlson, G. W. Boehlert, S. Urawa, Y. Ueno, and G. Anma, Diurnal variation in the thermal environment experienced by salmonids in the North Pacific as indicated by data storage tags. *Fisheries Oceanography*, in review, 2000.

Waring, R. H., and J. F. Franklin, Evergreen coniferous forests of the Pacific Northwest, *Science*, *204*, 1380, 1979.

Weaver, J. L., P. C. Paquet, and L. F. Ruggiero, Resilience and conservation of large carnivores in the Rocky Mountains, *Conservation Biology*, *10*, 964-976, 1996.

Welch, D. W., Y. Ishida, and K. Nagasawa, Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): Long-term consequences of global warming, *Canadian Journal of Fisheries and Aquatic Sciences*, *55*, 937-948, 1998.

West, N. E., and M. A. Hassan, Recovery of sage-brush-grass vegetation following wildfire, *Journal of Range Management*, *38*, 131-134, 1985.

Zobel, D. B., A. McKee, G. M. Hawk, and C. T. Dyrness, Relationships of environment to composition, structure, and diversity of forest communities of the central western cascades of Oregon, *Ecological Monographs*, *46*, 135, 1976.

ACKNOWLEDGMENTS

Many of the materials of this chapter are based on contributions from participants on and those working with the

Pacific Northwest Workshop and Assessment Team
Philip Mote*, University of Washington
Douglas Canning, Department of Ecology, State of Washington
David Fluharty, University of Washington
Robert Francis, University of Washington
Jerry Franklin, University of Washington
Alan Hamlet, University of Washington
Blair Henry, The Northwest Council on Climate Change
Marc Hershman, University of Washington
Kristyn Gray Ideker, Ross and Associates
William Keeton, University of Washington
Dennis Lettenmaier, University of Washington
Ruby Leung, Pacific Northwest National Laboratory
Nathan Mantua, University of Washington
Edward Miles, University of Washington
Ben Noble, Battelle Memorial Institute
Hossein Parandvash, Portland Bureau of Water Works
David W. Peterson, US Geological Survey
Amy Snover, University of Washington
Sean Willard, University of Washington

Comments by the following reviewers are gratefully acknowledged: Ralph Alig, Robert L. Alverts, William Clark, Robert Emmett, Josh Foster, Steven Ghan, Michael Haske, John Innes, Linda Joyce, Kai Lee, L. Ruby Leung, Susan M. Marcus, Steve McNulty, Ron Nielson, Claudia Nierenberg, Michael Scott, Francis Zweirs; Coordinated comments by U.S. Department of Agriculture; Coordinated comments by US Department of Interior; Coordinated comments by US Department of Energy. Remaining errors are the sole responsibility of the coordinating author.

* Assessment Team chair/co-chair