Impactsof climate variability and change inthe Pacific Northwest

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Overview

Experience of the recent past illustrates the impacts that the climate variations have on the Pacific Northwest, and illustrates that there are both winners and loser when the climate is different from the "average." The mild winter and spring of 1997—98 saw an early snow melt, which strained regional water supplies during the summer and fall months. An especially warm and dry summer, coupled with the early melt, led to exceptionally low flows and high temperatures in many Northwest streams. These conditions in turn caused sever difficulties for salmon. However, 1997—98 also had benefits for the region, which avoided the damage and disruption caused by heavy snow fall and winter flooding during the previous two winters.

Climate is not a constant, and yet many aspects of human infrastructure and activities are planned with the assumption that it is constant. But what happens when climate produces a surprise? What if, furthermore, there are long-term changes in climate? Humans have altered the composition of Earth's atmosphere to such an extent that climate itself appears to be changing. The consequences of a changing climate may be beneficial for some places and activities, and detrimental for others.

This report describes the possible impacts of human-induced climate change and of natural climate variability like El Niño, focusing on the **water resources, salmon, forests, and coasts** of the Pacific Northwest (PNW). It has been prepared largely by the Climate Impacts Group (CIG) at the University of Washington. The CIG, under the direction of Professor Edward L. Miles, is an interdisciplinary group of researchers from the physical, biological, and social sciences working together to understand the impacts of climate variability and change on the Northwest.

Looking at the recent past, much of the climate history of the PNW can be described by a few recurring patterns. The strongest pattern highlights the tendency for winter climate to be either relatively cool and wet or relatively warm and dry. Cool-wet winters are generally associated with increased risks of flooding and landslides, abundant summer water supply, more abundant salmon, reduced risk of forest fires, and improved tree growth (except at high elevation). Warm-dry winters are often followed by summer water shortages, less abundant salmon, and increased risk of forest fires. The occurrence of the cool-wet or warm-dry winter pattern is influenced by two main climate variations in the Pacific Basin: ENSO (El Niño-Southern

Oscillation) primarily on year-to-year timescales and PDO (the Pacific Decadal oscillation) primarily on decade-to-decade timescales. ENSO and PDO cause variation sin snowpack and streamflow, and hence the ability to meet water resource objectives; with respect tot he region's water resources, ENSO and PDO can reinforce or cancel each other. In contrast, the response of forests and salmon is correlated more strongly with the PDO than with ENSO. The magnitude of seasonal anomalies of temperature and precipitation leading to the above effects is strikingly small, but these past anomalies enable us to calibrate the possible responses to long-term climate change.

Looking to the future, computer models of climate generally agree that the PNW will become, over the next half century, gradually warmer and wetter, with most of the precipitation increase in winter. These trends mostly agree with observed changes over the past century. Wetter winters would likely mean more flooding of certain rivers, and landslides on steep coastal bluffs. The region's warm, dry summers may see slight increases in rainfall, according tot he models, but the gains in rainfall will be more than offset by losses due to increases in evaporation. Loss of moderate-elevation snowpack in response to warmer winter temperatures would have enormous and mostly negative impacts on the region's water resources, forests, and salmon. Among these impacts are a diminished ability to store water in reservoirs for summer use, more drought-stressed tress leading to reductions in forested area, and spawning and rearing difficulties for salmon.

Knowing what changes might occur is only part of the challenge, however. This knowledge must make its way from the realm of research to the realm of decisions, *and be used in decisions.* Large practical and, in some cases, legal constraints prevent climate information from being fully utilized. Meeting the challenges posed by climate variations and climate change will require considerable revision of the policies and practices concerning how the region's natural resources are managed. An indication of the scope of such revisions comes from considering how government agencies have handled climate-related stresses in the past, like droughts and coastal erosion. In many cases, agencies cannot even make use of a good seasonal forecast in making short-term planning decision: the operating assumption is often that climate is constant and extremes do not occur. There are wide variations among the four sectors considered here in how management presently makes use of climate information.

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Introduction

1

Part

Climate variations in the past have had a tremendous impact on the course of human history, at times allowing one civilization to flourish and at other times driving another civilization to migration or collapse. Even in this century, droughts and floods have crippled one region after another. Adding to these natural variations in climate, it now appears that humans have embarked on a global-scale modification of Earth's climate by substantially changing the composition of the Earth's atmosphere [72].

Our understanding of the potential consequences of future anthropogenic (human-caused) climate change rests squarely on our understanding of the consequences of past (natural) changes in climate. In this report we examine and, where possible, quantify the connections between past climate variability and changes in some of the Pacific Northwest region's natural resources. With these connections as a basis, we examine scenarios of future climate from climate models and assess the impacts such future climates would have on the Northwest. We focus both on past climate variability and on future anthropogenic climate change (the latter will be hereinafter abbreviated "climate change").

1 Pacific Northwest region

The impacts of climate change, and the ability to adapt to such changes, are best understood at the regional (sub-continental) scale. This is because the impacts of climate variability and change are not just biological but also deeply involve human institutions, nearly all of which operate primarily at scales smaller than a continent. Indeed, we consider climate impacts to be composed fundamentally of three elements: physical aspects of climate (temperature, rainfall, storminess, etc.), the natural resources influenced by climate, and the human institutions that manage or are in some way dependent upon those resources. These three elements interact on a variety of scales, but the regional texture of natural resources (e.g., the type of trees in a forest or the topography of a river basin) and of the institutions makes the regional scale perhaps the most constructive scale at which to assess the impacts of climate and the development of appropriate responses.

A short description of our study area —the Pacific Northwest (PNW) region—will provide important context for the discussions that follow.

1.1 Physical geography and climate

In this study, the PNW region is defined as the states of Idaho, Oregon, and Washington, and for some purposes we also consider the adjoining areas of the Columbia River Basin (Figure 1). The PNW has an exceptional diversity of natural resources and ecosystems, including coastal salt marshes and lowland freshwater wetlands, sandy beaches and rocky headlands, upland forest, and high mountain alpine environments [74]. The interior landscape of the PNW includes wheatlands and sagebrush desert in the eastern parts of Oregon and Washington; and the Rocky Mountains, high desert, and lava fields of Idaho. The natural environment of the region provides a large variety of outdoor recreation opportunities such as hiking, bicycling, boating, fishing, hunting, and skiing.

The natural vegetation of the region can be characterized by three main vegetation types [74] : forest, shrub-steppe, and alpine, but climatic variation across the PNW gives rise to many different plant communities and landscape patterns within these main vegetation types. Forests, for example, range from those that thrive in damp climates, like coastal Sitka spruce, to those that thrive in dry climates, like ponderosa pine and juniper. The degree of geographic and ecosystem complexity found in the PNW is unusual in the United States.

The Cascade mountain range divides the region geographically and climatically (Figure 2), and this divide plays a huge role in the water resources, salmon, and forests of the PNW. West of the Cascades, the lush low-lying valleys have a maritime climate with abundant winter rains (Figure 3), dry summers, and mild temperatures year-round (usually above freezing in winter, so that snow seldom remains for more than a few days). The mountains receive enormous quantities of rain and snow, exceeding 200 inches per year (water equivalent) at some locations on the Olympic Peninsula. At Paradise ranger station on Mount Rainier, Washington, the average year sees a maximum snow depth of 162 inches (4.1 meters), but in 1956 the snow piled up to 357 inches, nearly 30 feet (9.1m), during a year in which the total snowfall was 1122 inches (28.5m). Mount Baker, in the north Cascades, broke that record in 1998—99 with a total snowfall of 1140 inches (29.0m).

East of the Cascade crest, the climate is much more continental. As one passes the crest of the Cascades, rainfall

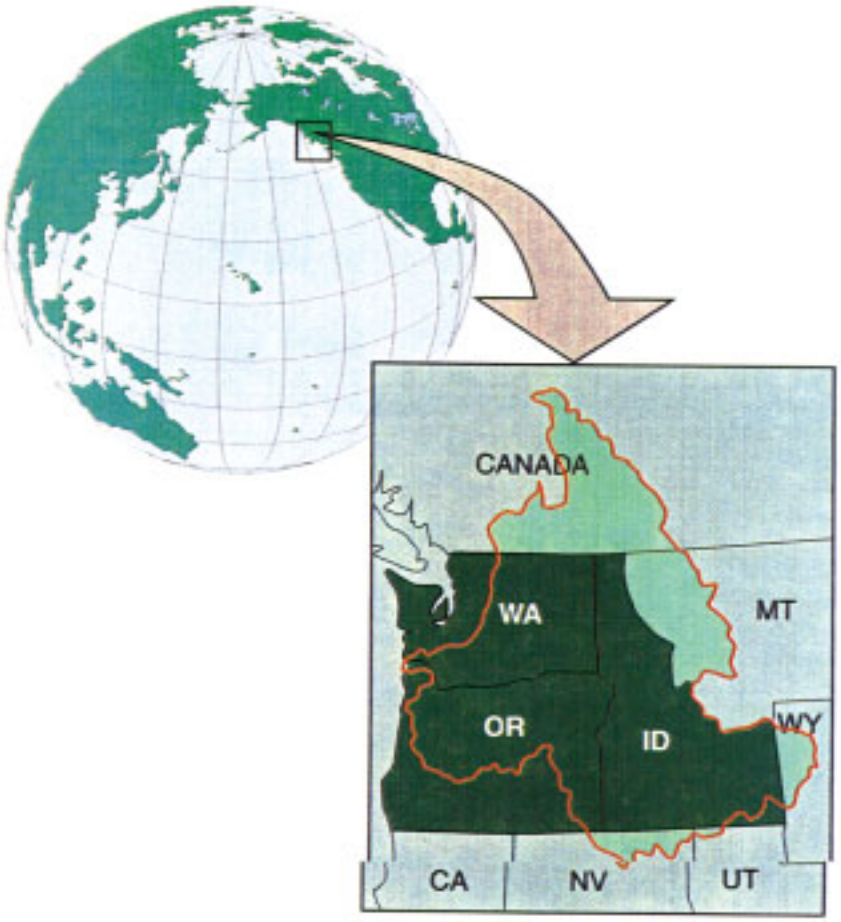

Figure 1. Map of the area studied: Washington, Oregon, and Idaho. The Columbia River Basin is outlined and lightly shaded.

and cloudiness become less common and sunshine and dry conditions become more common. Average annual precipitation is generally less than 20" (51cm), and some places receive as little as 7" (18cm), compared to more than 30" (76cm) in most places west of the Cascades. The annual and daily ranges of temperature east of the Cascades are considerably greater than those in the west. Winters are colder, with snow more common at low elevations, and summer days are hotter (though the nights are cooler). A greater fraction of precipitation falls in the warm half of the year, especially in May and June (Figure 3). The mountains east of the Cascade Crest—portions of the Rockies in Idaho, the Okanogan Highlands in Washington, and the Blue Mountains of northeastern Oregon and southeastern Washington—

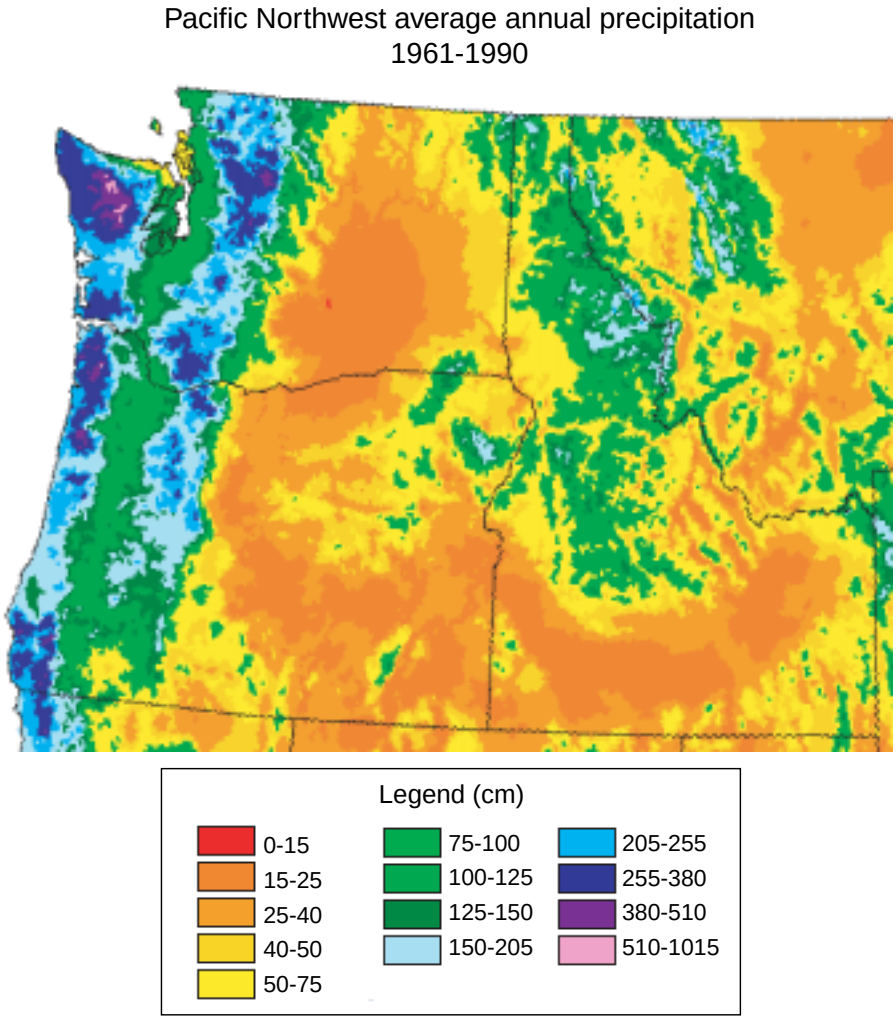

Figure 2. Average annual precipitation in the Pacific Northwest. The north-south Cascade mountain range divides the wetter west from the drier east. Figure courtesy of Oregon State Climatologist George Taylor.

receive much less precipitation than the western Cascade and Olympic Mountains.

1.2 Human geography

For the PNW region, the Cascade mountain range forms a cultural and economic divide, like the physical divide already noted. The majority of the region's population (72% in 1990) lives in the low-lying areas west of the Cascades. Most of the region's biggest population centers are west of the Cascades; the landscape and employment opportunities throughout the PNW are becoming increasingly urban. The once-dominant forestry and agriculture sectors in this area have given way to aerospace, trade, and services (especially computer

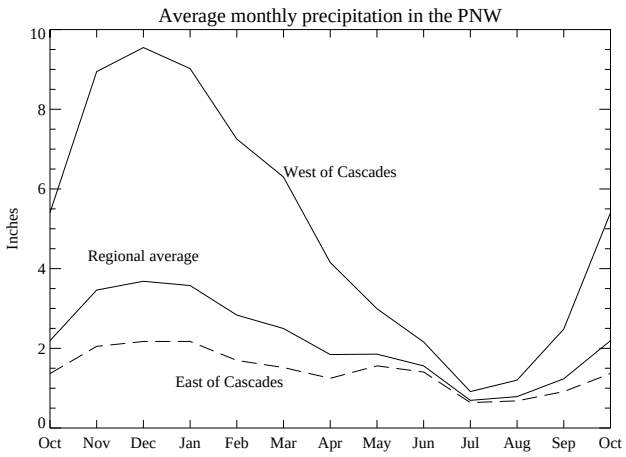

Figure 3. Annual variation of monthly average precipitation in the Pacific Northwest, both as a regional average and separately for the areas west and east of the Cascade crest. October is the first month of the hydrological "water year".

software), though the region still provides about half the nation's softwood lumber and plywood. Rural and agricultural lands play a more important role in the east. Thanks in part to massive irrigation projects, fertile lowlands in the Columbia Basin have made Washington the "Fruit Bowl" of the country, producing 60% of the country's apples ([156], 1996 figures) and large fractions of the country's other tree fruit. In addition, Idaho produces 27% of the nation's potatoes [156], also thanks in part to irrigation.

Population in the PNW has grown rapidly, and is expected to continue to do so (Figure 4a), with approximately double the population in 2040 that there was in 1990. (For details about the population scenarios, see Appendix D.) The regional average growth rate has been about double the national average since 1970. Using the Cascades as a division line (Figure 4b), it is clear that the populations on both sides of the Cascades are growing substantially and at roughly the same percentage rate, but with a larger population the west has a much larger numerical increase. Washington State, the most populous in the PNW with 56% of the region's population in 1990 (Figure 4c), is expected to have the largest growth rate both in numbers and in percentage. The rapid population growth is concentrated in the Puget Sound Lowlands and the Willamette Valley, and the smaller urban areas of Boise (Idaho) and Spokane (Washington) are experiencing rapid growth as well [74]. Population projections are for very large increases in every area of the Pacific Northwest, even in the lowest estimates. The baseline projection for the whole region calls for about 19 million people by 2050, a total increase of 80% from the estimated 2000 population. In just the next 20 years, the regional population is expected to grow by 34% or 3.3 million, with an increase of 2.5 million west of the Cascades. Growth rates over the last 30 years have varied considerably but have averaged about 2% per year (Figure 4d), close to twice the national average (not shown), and are expected to continue to while the NPA projections have the percentage growth rate declining over the next 50 years,

The impact of population growth is of fundamental importance in every regional environmental issue, including those discussed here. As we will see, in most cases climate change exacerbates the environmental stresses brought on by past human activities and those associated with the robust population growth in the Northwest.

1.2 Purpose of this report

Most scientific efforts to study changes in climate and their potential impacts (e.g., the Intergovernmental Panel on Climate Change) have been global or continental in scale, and the *regional}* impacts of climate change have not been adequately addressed. Furthermore, to date there has been little interaction between **scientists** studying global climate change and the **regional decision-makers** who will have to adapt to local manifestations of global climate change. For these reasons, the purpose of this report is to document the regional impacts of climate change on a few key sectors, and with this information construct a bridge between the large-scale science and regional adaptation.

Although the research presented in this report comes primarily from the UW Climate Impacts Group, it was motivated by and is part of the U.S. National Assessment of the Consequences of Climate Variability and Change (Appendix E). This is one of 18 regional assessments being conducted in support of the National Assessment.

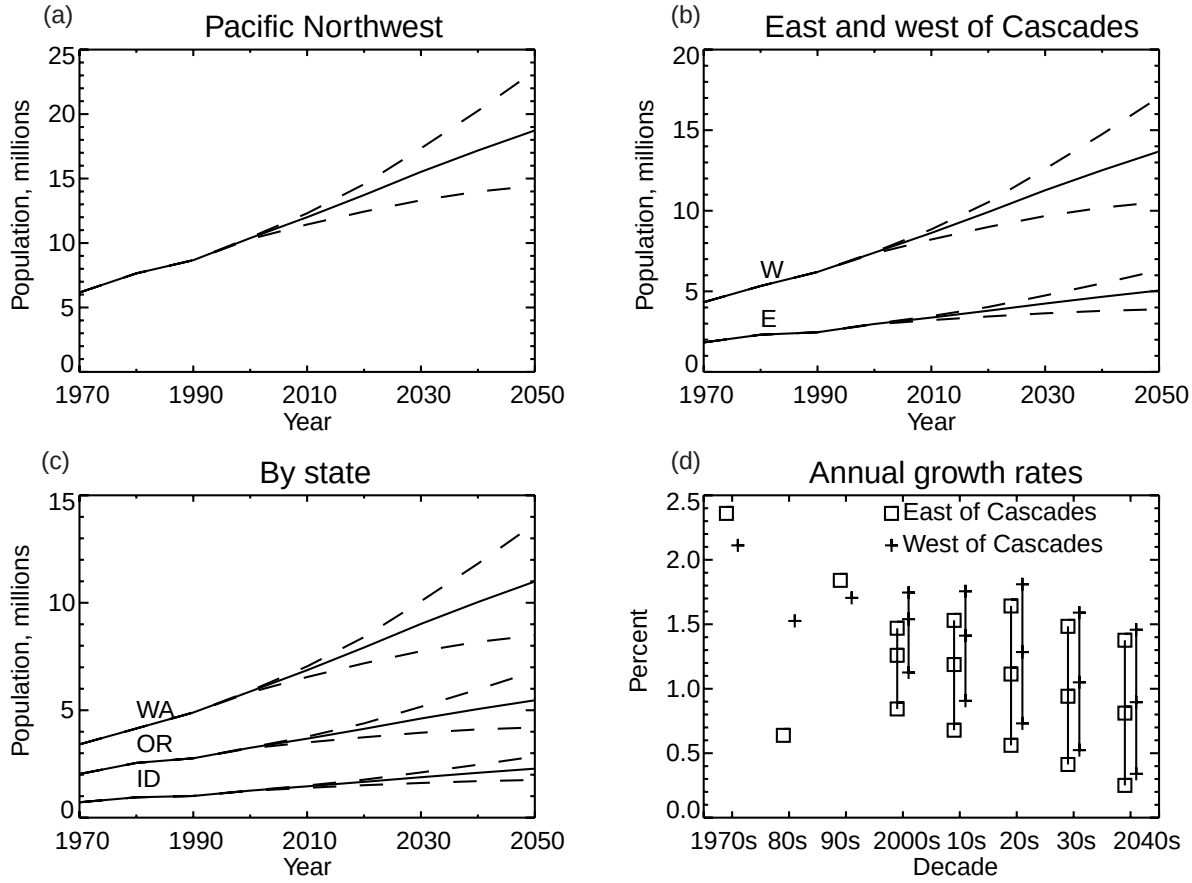

Figure 4. Population data and projections for the Pacific Northwest from NPA Data Services, Inc. (see Appendix D). Projections include baselines (solid) and high and low scenarios (dashed). In the lower right panel, symbols connected by vertical bars indicate the range of annual growth rates for the high, baseline, and low growth scenarios.

2.1 Workshop

In July 1997, the CIG held a workshop (which was sponsored by the National Oceanic and Atmospheric Administration, and also by the President's Office of Science and Technology Policy and the US Global Change Research Program) on the impacts of global climate change and climate variability on the Pacific Northwest. The workshop brought together scientists, regional policymakers, managers of natural resources, and many others to discuss the impacts of climate change. Eight sectoral topics were covered in the workshop:

- Hydrology and water resources
- Forests and rangelands
- Aquatic ecosystems
- Coastal activities
- Agriculture and grazing lands
- Human health effects
- Energy production and utilization
- Urban centers

These topics were chosen on the basis of their sensitivity to climate variations and their socioeconomic importance to the PNW. They also formed a basis for the four topics considered in detail in this report, where we focus on water resources (by far the most important), salmon, forests, and coasts. The decision to focus on four topics and to restrict the breadth of some of the topics (e.g., salmon instead of aquatic ecosystems) reflects in part the funding constraints and in part the existing expertise of the CIG. A new topic, human health, is already under investigation and will be included in future reports; we also hope to extend our work into the other sectors as well.

The presentations and discussions at the workshop are summarized in a report by Snover, Miles, and Henry [145], which is available from the Climate Impacts Group (tel. 206-616-5350). That report lists a large number of impacts, both positive and negative, of climate change on each of the eight topics listed above. It also suggests some coping options. Some of those impacts and coping options are discussed in the present document.

2.2 Outline

In this report, we describe the impacts of past climate variations on **water resources, salmon, forests, and coasts** in the Northwest, describe the future climate changes that may occur here, and suggest a few possibilities for adapting to those changes. The outline of the body of the report is as follows:

1. Regional climate
    - patterns of regional climate variation in the context of large-scale climate influences, PDO and ENSO
    - scenarios of future climate derived from climate models
2. Impacts of climate on each of the four topics (water resources, salmon, forests, and coastal zone)
    - current status and stresses
    - past changes and the observed impacts of climate variability
    - potential impacts of future climate change on natural resources
    - socioeconomic impacts of climate change
    - strategies for adaptation to climate change
3. Planning for the 21st century

2.3 Approach and scope

Throughout our study, our approach has been to use observed data to establish the impacts of observed climate variations on a variety of biophysical parameters, rather than simply to use simulations from a chain of models. That is, we establish empirically (and quantitatively where possible) the impacts of climate variability on key components of the physical, biological, and human environment in the Northwest. Not only do past data reveal biophysical relationships between climate variations and the region's natural resources, they also highlight the **response of human institutions to climate variability** and especially to extremes of climate, like drought.

This report does not seek to prove that climate change is occurring nor that it is due to human activities. Such questions are beyond the scope of this report, and fall under the purview of the Intergovernmental Panel on Climate Change (IPCC). The IPCC has issued a series of volumes representing the evolving state of knowledge concerning the character and impacts of climate change. In its 1995 Second Assessment Report (SAR), the IPCC concluded for the first time that "the balance of evidence suggests a discernible human influence on global climate." The SAR also projected a best-guess increase in global average temperature of 2.0˚C from 1990 to 2100. In this report, we accept the conclusions of the IPCC and make use of model scenarios of future climate that were generated as part of the ongoing IPCC process.

There are two key types of policy responses to scientific studies concerning climate change: mitigation and adaptation. Mitigation in this context means reducing the rate of climate change, and is a politically difficult subject that has completely dominated public discourse on climate change. The second response, adaptation, means considering in advance what changes may occur and taking those changes into account in short-term decision-making and long-range planning. This report does not make any recommendations concerning the *mitigation* of climate change, for example, whether or not the Kyoto protocol should be ratified. We do, however, suggest policy options concerning *adaptation*.

2.4 Defining sensitivity, adaptability, and vulnerability

Analyzing the impacts of climate variability or change on a system requires a consideration of how sensitive and how vulnerable that system is. The IPCC SAR [73] defines these terms as follows:

- *sensitivity*: "how will a system respond to given changes in climate?"
- *adaptability*: "to what degree are adjustments possible in practices, processes, or structures of systems?"
- *vulnerability*: "how susceptible is it to damage or harm?"

If a system is sensitive but also adaptable, then its vulnerability is low. As we shall see, the Columbia River water management system is moderately sensitive to climate variability and change but, because it is not very adaptable, its vulnerability is high.

2.5 Defining impacts

This report identifies patterns of climate variability and their relationships to water, fisheries, forestry and coasts. The first type of climate impacts, deriving from climate variability, are those observed physical or biological impacts that can be quantified either empirically or with numerical models. Translating these into societal impacts poses a series of other issues, however. There are two fundamental questions involved in assessments of societal impacts.

1. Do societies recognize the impacts that are identified through scientific research and, if not, why not?
2. Does climate variability affect society in any significant ways?

Other important questions should be addressed as well. Are these impacts perceived as positive or negative and does this perception differ among segments of society? What are the thresholds for having a significant societal impact? How has society already buffered itself from impacts? What if society is unaware of the impacts, yet research results demonstrate that they exist? Finally, given societal sensitivity and vulnerability to climate change, what are the barriers of policy, institutional design, and political will that constrain decision-makers in their use of additional information?

Not all of these questions are answered in this report. Human dimensions of physical and biological variability are not easy to assess and many have not been adequately studied. Here we report primarily on selected aspects of human dimensions, based on interviews with resource managers concerning management responses to climate variability (see Appendix B). We also identify other putative impacts based on logical extensions from those areas studied. For example, to date, some of the impacts of climate change on water resources are fairly well studied, but other topics are not, such as the impacts on ski areas of a rising snowline.

Similarly, identification of social impacts of climate variability involves indirect linkages and can only be studied by observing, over a sufficient period of time, how variations in climate translate into variations in production and consumption patterns for water, forest, fishery and coastal resources. Isolating the human dimensions of these changes is complicated by external forcing factors such as national and global markets for regionally produced goods and internal decisions about what to produce and how to produce it. We are at an early stage of quantifying social effects of climate variability. Most of the information presented here is based on retrospective analysis that is indicative but not conclusive. Nonetheless, it offers important clues from past experience about how climate affects human activities and what adaptation options may be effective.

2.6 Thresholds

In discussing thresholds in this report, we use one definition to fit both ecological and socioeconomic thresholds. This definition refers to the dependence of one variable y on another variable x.

> A threshold is a level (of x) beyond which there is a nonlinear or discontinuous response in an otherwise linear or continuous function y.

For example, a growing population with a fixed, but abundant, food supply can increase with relatively little impact up to the point where the food supply is (nearly) fully utilized. Further population increases can occur only if

everyone else gets less, and competitive interactions then become important. The point at which competition begins would be a threshold. The operating rules changed.A hypothetical example of a socioeconomic threshold might be the dependence of social disorder on unemployment. Suppose social disorder is relatively independent of unemployment for moderate rates of unemployment, but at some point further job losses may trigger mass protests, strikes, civil strife, and violent crime.

A more physical example of a threshold in the PNW concerns the flow on the Columbia River. Navigation is possible over a range of flow conditions, but at about 110% of the year's normal maximum flow, the current is too swift to permit navigation. Flood control systems are successful at preventing floods up to about 125% of the normal maximum flow, beyond which floods become much more likely.

Impacts of Climate Variation and Change

2

Part

Climate Variability and Change

1.1 Regional historical climate

The first step in evaluating the possible consequences of climate change is to characterize existing climate variability in the Northwest. We begin by showing in Figure 5 the annual mean temperature and precipitation for each year between 1900 and 1997, averaged over the whole region. (See Appendix A for a description of the datasets and analysis.) The average annual temperature is about 47˚F (8.2˚C), and the average annual precipitation is about 26” (66 cm). The standard deviation of interannual temperature variations is 1.15˚F (0.64˚C) and the range between the coldest (1916) and warmest (1934) years is 6.2˚F. Precipitation is more variable, with a standard deviation of 3.76” (9.5 cm) the wettest year (1996) is almost twice as wet as the driest (1929) year. Annually averaged temperature and precipitation are completely uncorrelated; there is no tendency for warm (or cold) years to be wetter or drier than average. Annual means can mask important seasonal anomalies whose impacts on natural resources can be profound; for example, an exceptionally dry summer can occur during a year with normal precipitation owing to the fact that most precipitation occurs in winter (see Figure 3).

Next, we ask two questions. First, what are the dominant patterns of climate variability in the region? Second, what external factors (e.g., El Niño-Southern Oscillation (ENSO) influence the region’s climate?

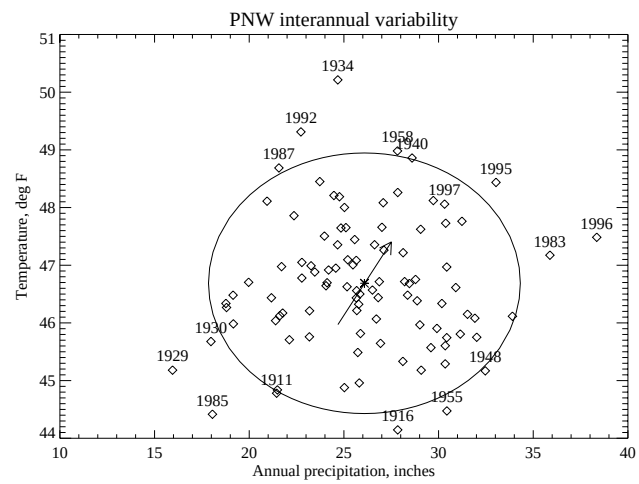

Figure 5. Scatterplot of annually averaged temperature (from Historical Climate Network data) and precipitation (from climate division data); see Appendix A for a description of the datasets. The ellipse shows two standard deviations in each direction from the mean climate of the 20th century (asterisk in the middle), and years that fall inside the ellipse are indicated only by a diamond symbol. The arrow indicates the linear trend for 1900—1997 (see Figure 10).

1.1.1 Dominant patterns of climate variability

Climate varies in both space and time, and our goal in answering the first question is to describe patterns in both space and time. It turns out that variations in time are

more important than variations in space; that is, by far the most common behavior is for all the temperatures in the region to be warm or cool at the same time, and likewise for precipitation. (Such statements do not apply to variations on short time scales like days or weeks, but only to variations of a month or more.)

The conclusion just stated was based on an analysis of climate division data (see Appendix A) using a computational tool known as EOF (for "empirical orthogonal function") analysis (see Appendix B.1). To simplify the analysis but still provide some detail, we use averages of temperature and precipitation over two halves of the year, October —March and April —September. In the "cool half" of the year (October—March), regionally averaged temperature and precipitation are uncorrelated (r=0.09), while in the warm half of the year they are anticorrelated (r=-0.40). That is, it is only in summer that warm years tend to be dry and cool years tend to be wet.

Having examined the simplest time variations of the regionally averaged data, we now examine the spatial variations. EOF analysis of cool-season data from all of the region's climate divisions reveals that the dominant pattern (i.e., the first EOF) of year-to-year temperature variations explains 84% of the variance and is regionally coherent. For precipitation, the dominant pattern explains 78% of the variance and is also regionally coherent. That is, there is a strong tendency for the regional climate to vary as a whole. **Variations in space (across the region) are less important than variations in time (of the whole region).** We take advantage of this regional coherence in our subsequent descriptions, ignoring for now the subtler spatial variations across the region.

Different types of variables can be considered together using EOF analysis to identify common patterns of variation in space and time (see Appendix B.1 for an example). When winter climate variables are expanded to include snowpack and streamflow, the result highlights fluctuations between warm-dry winters and cool-wet winters. Dell'Arciprete *et al.* [29] used time series of temperature, precipitation, sea surface temperature, streamflow, and snow depth to characterize year-to-year variations in winter using EOF analysis. Mantua *et al.* [101] extended the earlier analysis of Dell'Arciprete [29] performing EOF analysis on PNW "winter" (October through March) and "summer"(April through September) data using an expanded set of the same variables (temperature, precipitation, SST, streamflow, and snowpack - the last two variables for winter only). The first EOF for both winter and summer highlights the **see-saw tendency between warm-dry and cool-wet**. The second EOF is also the same for both seasons - cool-dry vs warm-wet - but in the summer pattern there is less spatial coherence, with the air temperature anomalies applying only near the coast and near Puget Sound.

As will be shown below, this pattern of climate variability (warm-dry versus cool-wet, a diagonal crossing the long-term trend in Figure 5) also characterizes the typical response of the PNW to Pacific-Basin climate variations associated with the El Niño-Southern Oscillation (ENSO) and with another, lesser-known pattern of Pacific climate variation known as the Pacific Decadal Oscillation (PDO).

1.1.2 ENSO and PDO

Both ENSO and PDO are patterns of Pacific climate that include changes in oceanic and atmospheric temperature, winds, and precipitation. ENSO is a natural cycle involving both the ocean and the atmosphere in the tropical Pacific. El Niño, the warm phase of ENSO, is a disturbance of the average tropical pattern of winds, temperatures, ocean currents, and rainfall, which in turn influences the atmospheric circulation in midlatitudes. La Niña (the cool phase) tends to produce a stronger version of the "normal" tropical circulation, and anomalies of tropical temperature, winds, and precipitation tend to be opposite to those of El Niño.

Like ENSO, PDO is a pattern of Pacific climate, but with several important differences. First, PDO appears to have its strongest signature in the North Pacific, instead of the tropical Pacific. Figure 6 shows the sea surface temperature (SST) anomalies, in color, that are associated with the "warm phases" of PDO and ENSO. Note the similarity of the patterns: warm near the equator and along the coast of North America, and cool in the central North Pacific. Note also the subtler differences in the patterns: ENSO has the largest variations in the tropics, while PDO has the largest variations in the central and northern Pacific. (The cool phases have the opposite patterns of SST anomalies: cool along the equator and the coast of North America, and warm in the central north Pacific.) The second difference between ENSO and PDO is that the timescales are different (Figure 7). ENSO tends to vary from one extreme to the other and back again within 2—7 years, rarely staying in the same state for longer than a year or two. By contrast, PDO tends to stay in one

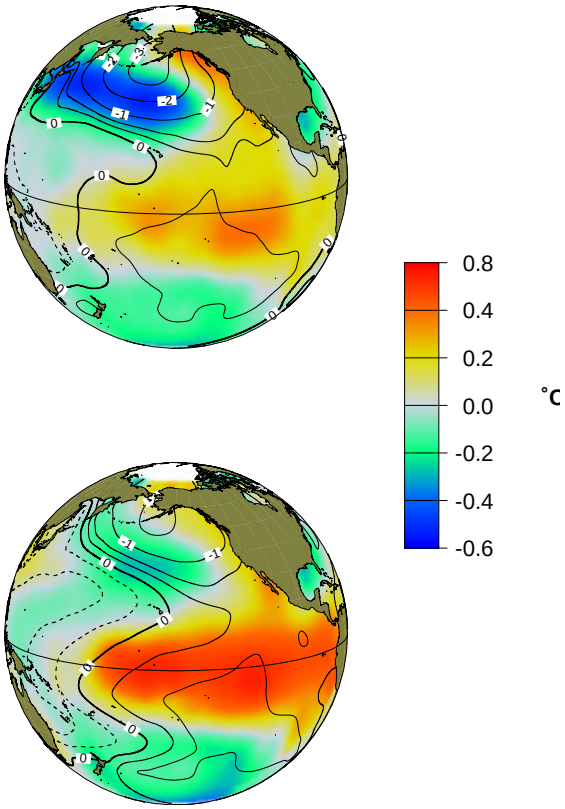

Figure 6. Spatial pattern of anomalies in sea surface temperature (SST; shading, degrees Celsius) and sea level pressure (contours) associated with the warm phase of PDO (top) and ENSO (bottom). The main center of action for the PDO is in the north Pacific, while the main center of action for ENSO is in the equatorial Pacific.

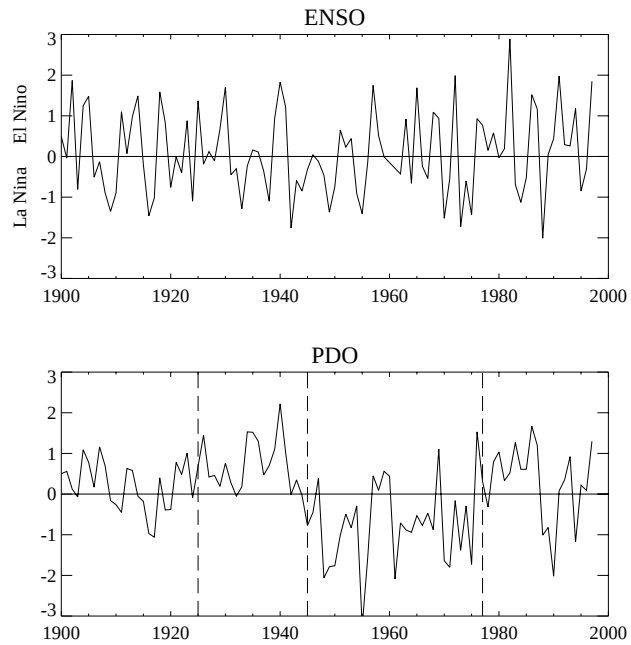

Figure 7. Time histories of the PDO and ENSO patterns from Figure 6. When the ENSO or PDO index is positive, the SST anomalies resemble those shown in the previous figure. When the index is negative, the SST anomalies are opposite, with red replaced by blue and vice versa.

phase or the other for 20—30 years. A third important difference between ENSO and PDO is in the state of the science: whereas ENSO has been extensively studied and is now routinely predicted at several centers around the world, the mechanisms of PDO are poorly understood and it is less predictable than ENSO.

The state of ENSO is often defined in terms of the sea surface temperature anomalies averaged over one of several boxes in the tropical Pacific [155]. A common choice is the "Niño 3.4" region, 5˚N—5˚S, 120˚W—170˚W, and we use it here. The PDO is defined using EOF analysis (see Appendix B.1), and is the dominant pattern of variation in the sea surface temperature of the Pacific Ocean north of 20˚N. The Niño3.4 and PDO indices are shown in Figure 7.

Part of the difficulty with understanding PDO is that its period is so long, compared to the period of good instrumental records in the north Pacific (since about 1900), that only about two complete cycles have been observed. It was in its **cool phase from about 1900 to 1925 and from 1945 to 1977. It was in the warm phase from 1925 to 1945 and after 1977. Another phase change may have occurred in the mid-1990's** but we cannot yet determine whether this is the case.

The reason that ENSO and PDO matter for the Northwest is that they influence the patterns of atmospheric circulation, which in turn affect weather in the middle latitudes. A prominent feature of wintertime climate in the North Pacific is a low-pressure area near the Aleutian island

	winter		summer	
	PC1	PC2	PC1	PC2
% var	41%	27%	41%	28%
PDO	**-0.64**	-0.04	**-0.45**	**-0.40**
ENSO	**-0.50**	0.03	**-0.26**	**-0.32**

Table 1. Results of EOF analysis of PNW climate for "winter" (Oct-Mar) and "summer" (Apr-Sep): percent variance explaine by each mode, and he correlation of the principal component time series with each season't PDO and ENSO index. Statistically significant correlations are shown in bold face.

chain that is known as the Aleutian Low. During winters when there is an El Niño event in the tropics, the Aleutian Low tends to be deeper (that is, the pressure is lower; see black curves in Figure 6). The Aleutian Low also tends to be deeper during the warm phase of the PDO. The Aleutian Low is part of the surface signature of the midlatitude storm track (the typical west-to-east path of storms); when the Aleutian Low is deeper than usual, the index storm track tends to split around the Northwest, with one branch bringing storms to Alaska and one bringing storms to California.

1.1.3 Impacts of ENSO and PDO on PNW climate

When the Aleutian Low is deeper, as it is during the warm phase of ENSO (El Niño) or the warm phase of PDO, the PNW tends to have slightly warmer, drier winters. Mantua *et al.* used the warm-dry/cool-wet pattern identified in their EOF analysis (see sectionB.1) to characterize the relationship between that pattern and ENSO and PDO. In this calculation (results shown in Table 1), the indices for ENSO and PDO are also divided into winter and summer. PC1 is the principal component time series (PC) for the first EOF, i.e., warm-dry vs cool-wet, and PC2 is the PC for the second EOF. In both halves of the year, the first two EOFs explain about 68% of the variance. The strongest correlation (-0.64) is between the winter cool-wet vs warm-dry climate pattern and the PDO; its correlation with ENSO is also relatively large (-0.50). The second winter pattern is uncorrelated with ENSO and PDO. The negative sign of the correlations indicates that for both ENSO and PDO, the warm phases (shown in Figure 6) show a strong connection to the warm-dry pattern in the first winter EOF. Likewise, the cool phases of ENSO and PDO also show a strong connection to cool-wet winters. Therefore, the PDO and ENSO play a significant role in determining the character of a given winter and to a slightly lesser extent the character of a given summer. It is noteworthy that summer anomalies are almost as well correlated with PDO and ENSO as winter anomalies, even though as Mantua *et al.* showed, the circulation patterns associated with the summer anomalies have much smaller spatial extent. It is also noteworthy that the PDO and ENSO response has subtle spatial variations (not shown), with the area west of the Cascades having generally a larger response than the area east of the Cascades.

Note that the correlations are far from perfect. This highlights an important point, one often overlooked when anticipating the impacts of an El Niño or La Niña event that has been forecast: The deviations in temperature and precipitation that accompany warm or cool ENSO events are not always the same—in fact, in any given location there are examples of winters that defied the pattern.

The climate response in the PNW appears to depend on the strength of the ENSO event (as measured by SST anomalies near the equator, the so-called "Nino3.4" [155]; see page 14), but not in a way one might expect. Instead of simply intensifying the warm-dry pattern, stronger El Niño events may steer the circulation toward a simply warmer pattern. The strong El Niño events of 1982—83 and 1997—98 were marked by above-normal temperatures but near-normal precipitation, leading to smaller anomalies in snowpack and streamflow than those for an average-intensity El Niño event. A composite of the atmospheric circulation for strong El Niño events shows notable differences from a composite for moderate El Niño events: In the strong events, the Aleutian Low is deeper and farther east, bringing more warm, moist air into the PNW. As will be shown later, this is precisely the pattern that at least two climate models suggest will become more prevalent as climate change progresses in the next century.

1.1.4 Long-term trends

Before considering climate projections for changes in the next century, it will be useful to see how climate has changed in this century (without ascribing a cause to such long-term changes). We first show the trends in temperature (Figure 8)

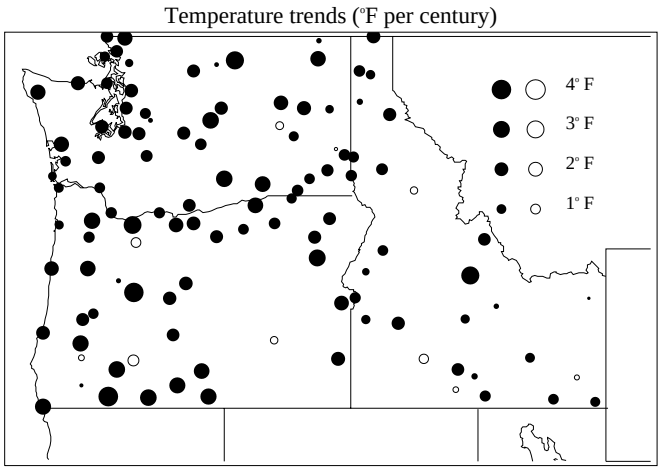

Figure 8. Trends in annually averaged temperature at 113 Historical Climate Network stations (see Appendix A for details). Open circles indicate negative trends and the area of the circle is proportional to the magnitude of the trend.

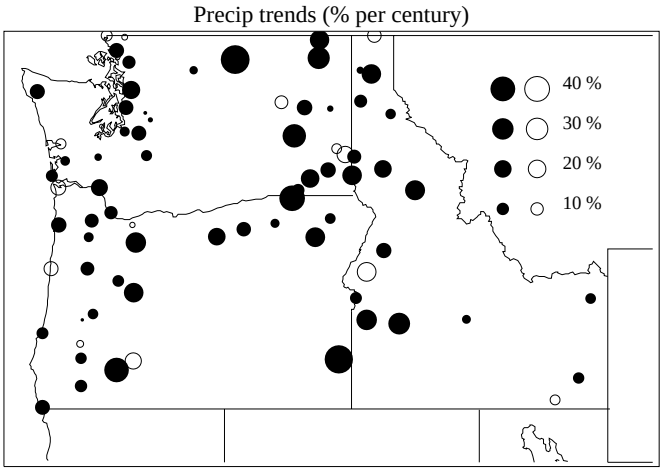

Figure 9. Trends in annual total precipitation at 76 stations, expressed as a percentage of their 1961—90 mean precipitation.

and precipitation (Figure 9) at each of the Historical Climate Network (HCN) stations in the PNW. Few stations have negative temperature trends and most have trends between 1˚F and 3˚F (0.6 - 1.7˚C). The precipitation trends are also overwhelmingly positive, and in many cases quite large, with substantial relative increases most common in eastern Washington and eastern Oregon. At some stations west of the Cascade crest with high annual precipitation, these percentage increases correspond to very large absolute increases (not shown); the largest absolute trend is +19.7” (50.0cm) per century at Three Lynx, Oregon, in the Cascade foothills east of Salem.

Figure 10 shows the average annual temperature and precipitation in the Pacific Northwest (using HCN data, the same data as were shown in Figure 5). The temperature trend is +1.48˚F over the 20th century, statistically significant at the 99% confidence level. Part of this trend is due to the PDO; the century began in the cool/wet phase and most of the last 20 years have been in the warm/dry phase. When the influence of the PDO is removed from the temperature data at each station by statistical regression, the resulting trend is +1.16˚F. This is slightly greater than the global average trend during the 20th century (0.9˚F, [72]). Separate winter and summer trends (not shown) are nearly equal, in contrast to the general finding for many places that winter temperatures are rising faster than summer temperatures [72].

The linear trend in precipitation is +2.8” per century (an increase of 14%), whereas the pattern of PDO phases (cool-wet at the beginning of the century, warm-dry for much of the end of the century) would by itself have led to a negative trend.

Figure 11 shows the annual average temperature and precipitation again, only this time instead of the trends, the averages over the phases of the PDO are shown. Note the breakpoints at 1925, 1945, and 1977. The sizes of the jumps between the horizontal lines are indicated in table 2.

1.1.5 Paleoclimate

It is also useful to consider variations in climate from the more distant past. Reconstructions of past climate from tree-ring data (calibrated against instrumental records) present conflicting pictures of climate variability before the instrumental records began. A study of 41 drought-sensitive conifers in Washington, Oregon, and Northern California [56] suggested that severe droughts like the ones in the 1920s and 1930s (see Figure 10) have occurred about once per century. However, that study also showed 1889 to be the driest year in the Columbia River basin, whereas our analysis of

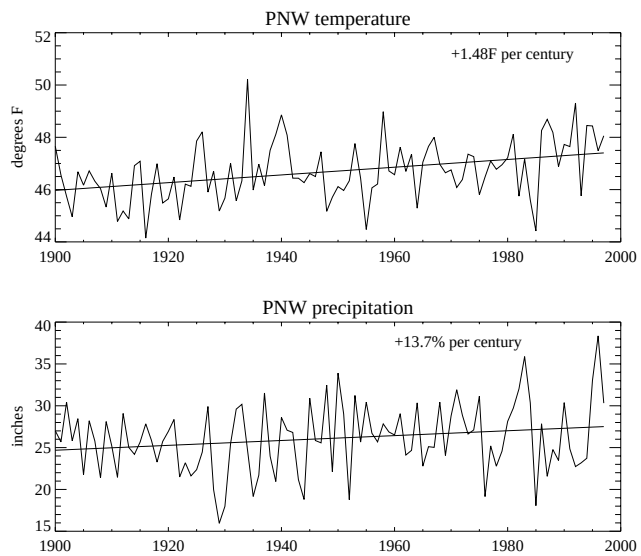

Figure 10. Plots of temperature and precipitation, along with long-term linear trends.

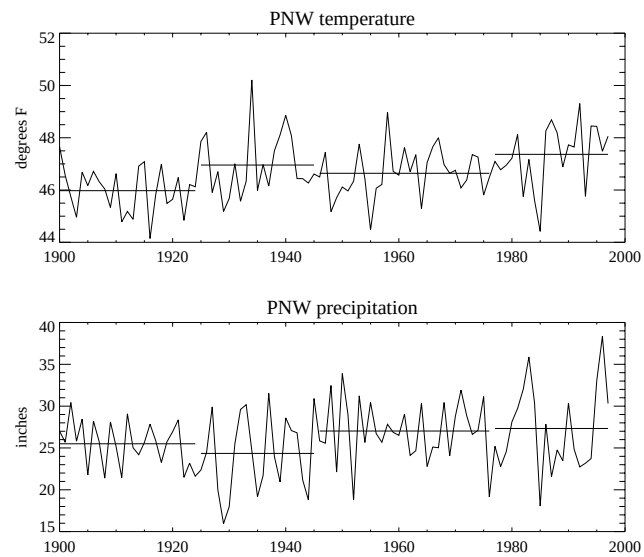

Figure 11. Plots of temperature and precipitation, with horizontal lines indicating the averages over opposite phases of the PDO.

Columbia River flow (at The Dalles, corrected for the changes in flow brought about by dams) shows 1889 had only the ninth lowest flow of the 1879—1997 period.

Crater Lake in southwestern Oregon, "the world's largest rain gauge", seems to be at lower levels now than at any time in the last 300 years except the early 1930s to mid-1940s [128]. Tree-ring analysis was used to reconstruct precipitation and lake level, and the reconstructed quantities agree fairly well with the observed quantities during this century. The results indicate a long-term decline in both precipitation and lake level going back to 1700 [128]. This result cannot, however, be generalized beyond the location of Crater Lake, since nearby Prospect, Oregon and most other Oregon stations show positive trends during this century (Figure 9; Crater Lake and Prospect are represented by the pair of large circles in southwest Oregon, one open and one filled, that are touching each other).

Another tree-ring study, this one conducted by our group [30], indicates that the warm-dry period of 1925-1945 was the warmest and driest in the PNW during the last 250 years. This study used 31 chronologies of subalpine mountain hemlock

	1925	1945	1977
ΔT, $^{\circ}F$	0.95	-0.33	0.66
Δp, %	-1.54	9.87	-1.59

Table 2. Shifts in temperature (top) and precipitation (bottom) between phases of the PDO. Temperature data are from the HCN dataset and precipitation data are from the CD dataset.

in Washington and Oregon. Given the complex way in which tree rings respond to climate and the differences between tree species used by these two studies, the results may not in fact be in such sharp disagreement about the uniqueness of the 1925-45 period. Further work is needed to elucidate the behavior of climate over the past several hundred years; the results could have important implications. For example, if the 1925-45 period turns out to be the driest in the last 400 years, instead of the last 100, then a water management system designed to endure the 1925-45 period could be expected to be resilient to a more extreme drought than is likely to be encountered in 100 years in an unchanging climate. Of course, evidence is mounting that we do not live in an unchanging climate.

1.2 Possible future climate

Over the coming decades, the climate of the PNW will certainly continue to be influenced by climate conditions over the Pacific basin, but the future behavior of ENSO and PDO is uncertain. In the near term, it is possible that a PDO reversal has occurred, back to the "cool" phase; if the PDO behaves as it has in the past, then the PDO could, for a while, mask or diminish the long-term warming trend that was noted above but could accentuate the long-term trend toward more precipitation. Indeed, the 1996—97 and 1998—99 winters were unusually wet in much of the PNW.

In any case, there is no doubt that year-to-year variability will continue to be an important part of future climate. Whether and how much the average temperature and precipitation change in the next century, extreme events—floods, droughts, heat waves, cold snaps—will continue to play a pivotal role in the way humans and ecosystems experience the impacts of climate. Therefore, the reader should bear in mind, as we discuss changes in average climate, that changes in the averages are only a part of the story.

Quantitative insight about possible future climate is gained from elaborate computer programs, called climate system models (abbreviated here "climate models"), which represent the physical interactions of energy and mass in the atmosphere, oceans, and land, over the entire globe. With climate models, one can explore fanciful possibilities like the climate of a world without mountains, or of realistic possibilities like the climate of a world with twice the atmospheric carbon dioxide (CO_2) concentration of today's world. Climate models are similar to the computer programs used for forecasting the weather, but are significantly more comprehensive than weather prediction models because they also simulate interactive changes in oceans, sea ice, land surface, and in some cases vegetation and atmospheric chemistry. Climate models also have a significantly different goal. Whereas the success of a weather forecast depends on the prediction of the exact state of the atmosphere at a given time, climate-change scenarios describe only the statistics of climate (annual average surface temperature, for example) over a longer period of time.

In this study we focus on three time horizons: the decades of the 2020's, 2050's, and 2090's. The climate scenarios for these decades are taken from simulations that depend on emissions scenarios represented by a simple 1% per year increase in equivalent CO_2. It is common to treat the growth of all greenhouse gases in this way, overestimating the true increase in CO_2 but neglecting the increases in other greenhouse gases like methane, nitrous oxide, and chlorofluorocarbons. Estimates of future emissions are very uncertain because they depend on estimates of future economic growth, changing energy use, and policy. Consequently, *the quantitative results presented here are not predictions of what will happen but scenarios of what might happen* given continued, unrestrained growth in emissions of greenhouse gases. The scenarios are also constrained by the shortcomings of the models, primarily in the way various physical processes are treated. Furthermore, the final time horizon (the 2090s) should not be taken as a final state of the Earth's climate: it is quite possible that the concentrations of greenhouse gases will continue to grow beyond 2100, leading to further changes in climate.

1.2.1 Climate models used

The UW Climate Impacts Group has examined output from two generations of climate models, and has also made use of a simulation using a regional climate model. The three models in the older generation, in 1995, were those from the Max-Planck Institut für Meteorologie (MPI), the U.K. Meteorological Office Hadley Centre (HC), and the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). The four models in the newer generation, in 1998, were those from the Canadian Centre for Climate Modeling and Analysis (CCC), as well as newer versions of the HC, MPI, and GFDL models. Two primary differences between the older and newer

generations were the detail of processes represented and the emissions scenarios used. Each of the models in the older generation consisted of an elaborate model of the atmosphere and fairly simple models of oceans, sea ice, and land surface processes. The models in the newer generation included more elaborate models of ocean, sea ice, and land surface processes. The emissions scenarios were also different: the older generation used scenarios in which only CO_2 changed, but the newer generation included changes in sulfate aerosols, which have a cooling effect on parts of the planet's surface and are represented in the models by increased atmospheric albedo (reflectivity).

This report focuses on results from the HC and CCC models, partly because those are the models that are used in the National Assessment (see Appendix E). The climate scenario from the CCC model was available earlier than the other models and receives more attention here because processing a regional subset of CCC output as a long time slice is much easier. However, among the new generation of GCMs, including several that we have not examined in any detail here, the CCC model has one of the highest rates of globally averaged warming given the same greenhouse gas emissions scenario, especially late in the next century. (For global average temperatures, the HC model gives a more moderate projection of future changes.) The CCC simulation presented here also used a more primitive land surface model than the HC and other models.

Researchers at the Pacific Northwest National Laboratory (PNNL) have produced regional climate scenarios with a regional climate model (PNNL-RCM) with winds, temperature, and moisture fluxes at the boundaries taken from two climate simulations with the National Center of Atmospheric Research (NCAR) Community Climate Model (CCM3). For the control simulation, the CCM3 atmospheric model used specified sea surface temperature (SST) and sea ice conditions of the 1990's. In the climate change scenario, CCM3 used SST and sea ice conditions generated by the older generation GFDL coupled atmosphere-ocean model with CO_2 concentration increasing at 1% per year until it doubles compared to 1990 (about 2060). By using a subgrid method to represent orographic precipitation, PNNL-RCM was used to produce climate scenarios at 1.5km spatial resolution over the PNW.

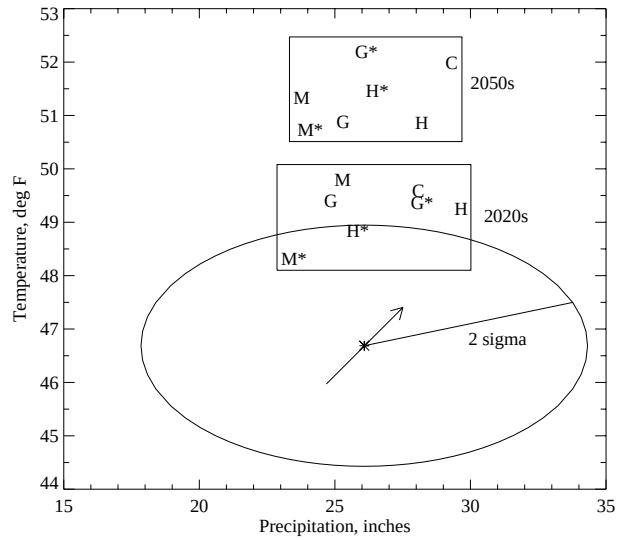

Figure 12. Changes in climate over the Columbia River Basin for the 2020s and 2050s from seven climate model scenarios. The large asterisk and arrow show the mean PNW climate and trend for the 20th century from the data shown in Figure 5. Each letter indicates the decadal mean for one climate model simulation. The letters H, C, M, and G refer to the HC, CCC, MPI, and GFDL models, and an asterisk indicates that the model was from the 1995 generation. Boxes are drawn around the scenarios for each decade.

1.2.2 Summary of model results

Figure 12 shows the decadal average changes in temperature and precipitation (relative to their own pre-industrial climate) from several climate models for the Columbia River basin, downscaled to a 1˚ grid using the VIC hydrology model (see Appendix C). Also shown are the mean (asterisk) of 20th century observations (as in Figure 5) for the PNW and an ellipse indicating the range of two standard deviations in each direction, where the standard deviation is calculated from 20th century observations after detrending the data. All the model simulations show substantial increases in temperature by the 2020s, but the range of decadal average precipitation falls within the current range. There are no striking differences between the two generations of models.

A warmer, wetter climate would have a number of benefits for the Northwest, but the seasonality of the precipitation changes suggested by the models is not as beneficial. Considering now two halves of the year separately (Oct-Mar and Apr-Sep), we find that **the models are generally in agreement that winters will be warmer and wetter, but are divided about whether summers will be wetter or drier**. Figures 13 and 14 summarize the changes in temperature and precipitation, relative to a control simulation with pre-industrial concentrations of greenhouse gases. The figures show results for each model simulation separately and for the average of all the simulations (bold curves). For the decade of the 2020s, the models suggest an increase in annual average temperature of 3.1˚F, and except for the old HC run (boxes, dashed) the models show no significant seasonal variation of the changes and no substantial differences between the 1995 and 1998 models. For the 2050s, the average increase is 5.3˚F and again there is no significant seasonal variation of the changes. The lack of seasonality in PNW regional temperature changes is in considerable contrast to the global average changes in temperature suggested by the models, in which winter temperatures rise more than summer temperatures.

Both generations of models tend to produce somewhat wetter winters and somewhat drier summers, although the HC model (boxes) produces much wetter summers than the other models (Figure 14). Because of the strong seasonality in precpitation in the PNW (see Figure 3), even the largest percentage changes in summer are roughly equal, in absolute precipitation amounts, to the small percentage changes in the winter. The seasonality of the average change is more pronounced in the 2050s, but in both the 2020s and the 2050s the average annual precipitation increases about 5%. Notably, the increase in annual precipitation in these scenarios does not lead to more available water, as we will show later.

The changes in winter climate are associated with a dramatic change in the atmospheric circulation over the Pacific that is nearly the same for both the CCC and HC models: a deepening and southward shift of the Aleutian Low, displacing the storm track southward and giving the mean wind at the Pacific coast a stronger and more northward component (Figure 15), much like the situation during strong El Niño events like 1982—83 and 1997—98. Warm, wet storms are apparently much more common in these scenarios toward the end of the next century.

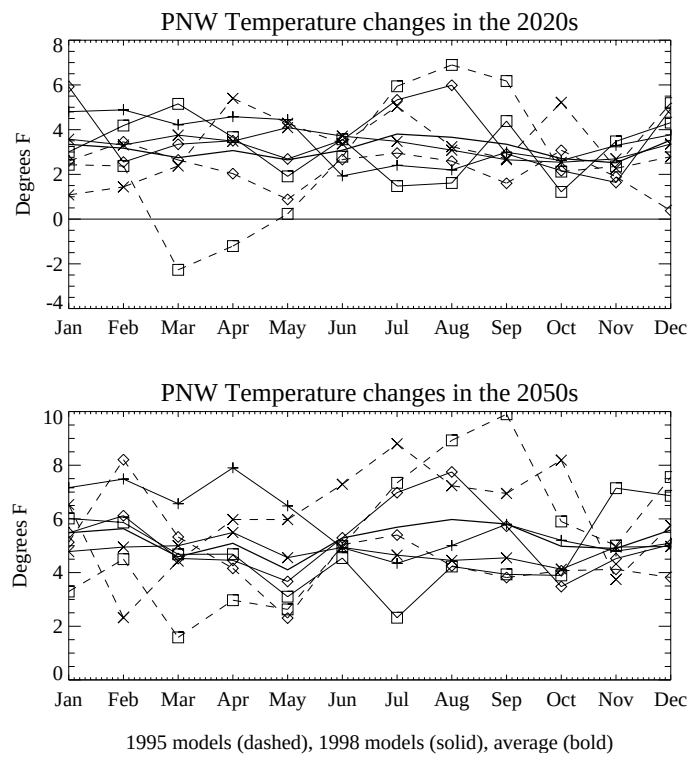

Figure 13. Changes in temperature, averaged over the Columbia River Basin, as simulated by three atmospheric models in 1995 (dashed curves) and by four climate system models in 1998 (solid curves). The symbols stand for different models: boxes represent UKMO and its relative the HC model, diamonds represent MPI, crosses represent GFDL, and plus symbols represent CCC. The bold curve is the average of all seven models for each month.

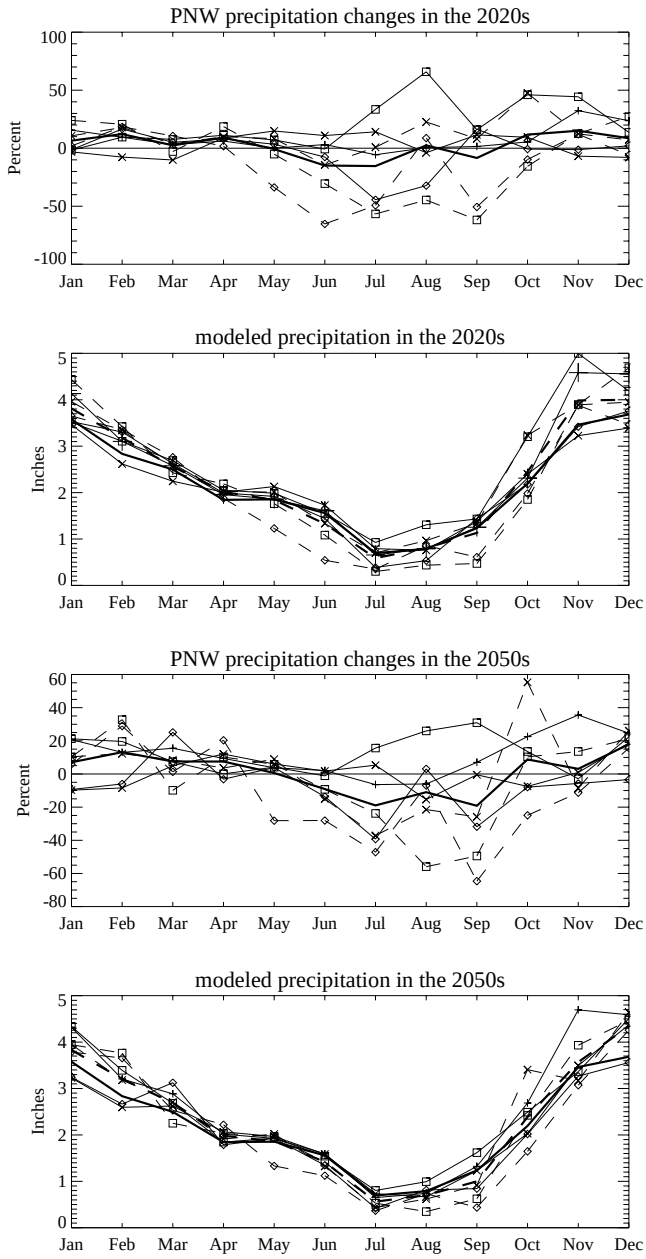

Figure 14. Changes in precipitation from several climate models for the 2020s (top two panels) and 2050s. Changes are shown both as a percentage of modeled values for base-case climate (i.e., CO_2 at pre-industrial levels) and with those percentages applied to climatology (Figure 3). Legend as in Figure 13.

2020s

		Precip change, inches	
model	temp chg	Apr-Set	Oct-Mar
CCC	1.95°C (3.51°F)	0.15	3.02
HC	1.76°C (3.16°F)	1.28	3.45
MPI	2.06°C (3.71°F)	-0.27	0.57
GFDL	1.81°C (3.31°F)	0.82	-0.90
MPI*	1.24°C (2.23°F)	-2.51	0.84
HC*	1.53°C (2.75°F)	-1.73	2.47
GFDL*	1.81°C (3.27°F)	0.40	2.71
average	1.74°C (3.14°F)	-0.27	1.57

2050s

		Precip change, inches	
model	temp chg	Apr-Set	Oct-Mar
CCC	3.28°C (5.90°F)	0.27	4.13
HC	2.65°C (4.77°F)	0.76	2.52
MPI	2.92°C (5.25°F)	-0.84	-0.37
GFDL	2.66°C (4.79°F)	0.27	0.10
MPI*	2.58°C (4.64°F)	-1.77	0.70
HC*	2.99°C (5.38°F)	-1.07	2.53
GFDL*	3.39°C (6.10°F)	-0.75	2.81
average	2.92°C (5.26°F)	-0.45	1.35

Table 3 Changes in PNW climate for various climate models. Area-averaged fractional changs in precipitation from the GCMs are applied to observed seasonal precipitation to derive quantity changes. Asteriks denote the older generation of models (see section 1.2.1 for explanation).

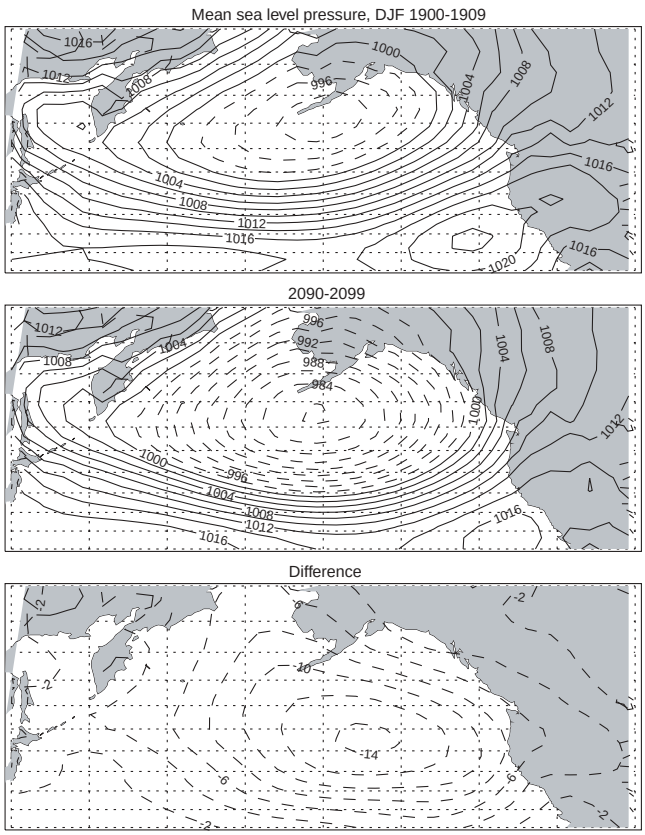

Figure 15. Sea level pressure field simulated by the HC model, 1900's (top), 2090's (middle), and the difference (bottom). Contour interval 2 mb, dashed contours represent pressures below 1000 mb in the top two panels and represent pressure decreases in the bottom panel.

The models have biases (systematic errors) in the climate that they simulate for the PNW, leading to questions about whether the trends projected for the 21st century are reasonable. To this, we make a few relevant observations:

1. Regional changes need not proceed at the same rate as globally averaged changes.

2. The climate models are fairly well able to reproduce the slight increase in globally averaged temperature during this century, though not the warm period in the 1930's. They have done very well at simulating the period since 1970, when forcing by greenhouse gases has apparently grown to dominate over natural causes of variations (e.g., [151]).

3. The GCMs are fairly consistent in the temperature changes they suggest.

4. We use the GCM output not as a prediction for mean conditions in a certain decade but as a scenario.

1.2.3 Details of the CCC model run

To give an indication of how one model scenario unfolds in time, we compare (Figure 16) observed temperature trends in the PNW from 1900 - 1997 with those simulated by the CCC. This model produces a climate that is too warm in the cool season and too cool in the warm season—in short, milder than observed. One important reason for this is that the CCC (and indeed all the climate models) has such coarse horizontal resolution that the topography in the model resembles a broad, gently sloping plain rising toward the Rockies. As a consequence, the climate of the PNW in the model varies quite gradually from maritime in the west to moderate-elevation continental in the east, in contrast to the sharp divide noted above between the maritime climate west of the Cascades and the continental climate east of the Cascades. Since most of the PNW lies east of the Cascades, it has a more continental climate than the mostly maritime climate in the CCC.

The model does better with *trends* in temperature than with temperature itself. Observed trends are about 1.5˚F/century in the warm season and 1.3˚F/century in the cool season, fairly close to the modeled trends (1.1˚F/century and 2.2˚F/century).

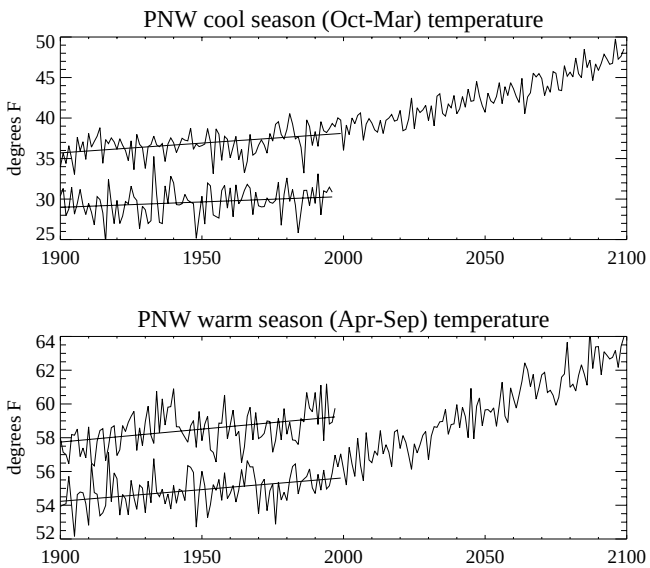

Figure 16. Average PNW temperatures for the cool and warm halves of the year. The light curve shows values from the CCC climate model, and the heavy curve shows observed values. Linear trends of the 20th century are shown as straight lines. Because the model ran freely with no input from observations, we would not expect a year-to-year correspondence between the model and observations.

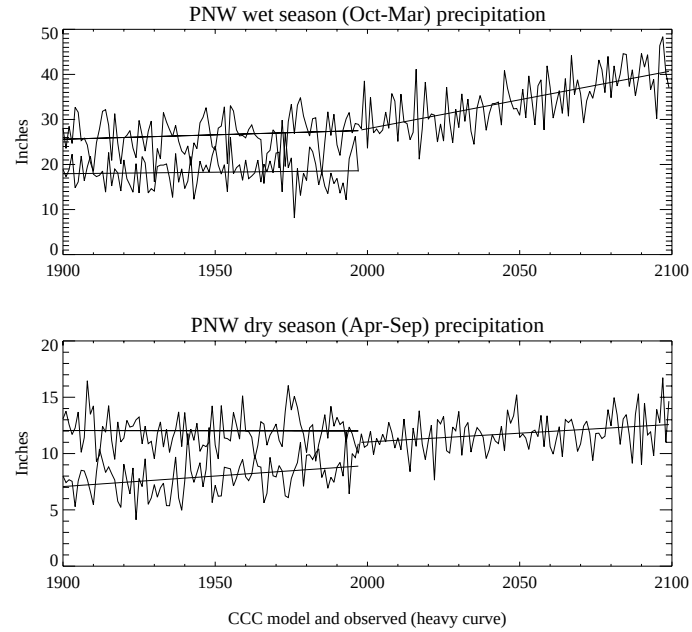

Figure 17. Average PNW precipitation for the indicated months, from the CCC run (light curve) and observed (heavy curve) along with linear trends for each century.

As for precipitation, the CCC model produces nearly 50% more rainfall over the region than is observed (Figure 17), consistent with the maritime character of the model's climate. (In the hydrological modeling presented below, and in the results shown in Figure 12, the biases in temperature and precipitation have been removed; (see Appendix B.) The observed wet season trends are roughly in agreement (4%/century observed, 7%/century modeled) but the observed dry season trend is 26%/century while the model trend is almost exactly zero over the same period (and, in fact, over the whole 200-year simulation as well.)

An indication of the degree to which these results depend on the resolution of the model comes from climate-change simulations [88] comparing the CCC with a regional climate model. This comparison suggests that the spatial distributions of changes in temperature and sea-level pressure are less sensitive to resolution than changes in the spatial distributions of precipitation, soil moisture, and snowpack.

In the CCC, the wintertime warm bias and warming trend are enhanced by a gradual (but complete) loss of snowpack. The highest grid point in the PNW, at 5800 feet, is the last to lose its snowpack, and this occurs at about year 2070 of the simulation. Because of the warm bias and other reasons, we do not believe this is a realistic scenario for the 21st century. Below, we will examine changes in snowpack in more detail using more suitable models, in some cases with biases corrected.

1.2.4 Details of the regional (PNNL-RCM) model run

The regional model described in section 1.2.1 was used to add finer texture to the picture presented by the several global climate models. The control regional simulation does slightly better than global climate models over the PNW [95]. The simulation is about 20% too wet and 2.7˚F (1.5˚C) too cold during winter. In the summer, the

simulation is about 50% too dry and 2.0˚F (1.1˚C) too warm. These biases demonstrate that regional models are not necessarily vastly better than global models.

In the climate change scenario at about the time of CO_2 doubling [96], precipitation generally increases during the cool season, and decreases slightly during the warm season. However, the precipitation signal is only statistically significant during spring (about 30% increase) when both the change in the large-scale circulation and increase in water vapor enhance the moisture convergence towards the north Pacific coast. Annually averaged surface temperature increases by about 4˚F; the warming is 2—2.5˚F greater during the cool season than the warm season.

The combined effects of temperature and precipitation changes cause a significant reduction in regional snowpack. Figure 18 shows the spatial distribution of snow water equivalent in the climate change simulation as a percentage of the control simulation. Snowpack is typically reduced by about 30% over the Northern Rockies, and by about 50% over the Cascades range. Reductions of 50% to 90% are found near the snow line of the control simulation. By analyzing the climate signals over a large elevation range from sea level to 14,000 feet, we find that changes in surface temperature and snowpack have a strong dependence on elevation because of changes in the altitude of the freezing level.

1.2.5 Future variability of Pacific climate

PDO and ENSO (see section 1.1) are important factors influencing the climate of the PNW. State-of-the-art climate models are increasingly able to represent ENSO, but are farther from producing decadal variations of the magnitude and character observed. Even if climate models demonstrated an ability to faithfully generate natural climate variability (like that observed in the 20th century), their ability to predict how ENSO and PDO might change in a warming world would still be in question. In one climate model, the magnitude of the ENSO cycle increases abruptly at some point in the future [152]. Of the models used here, the tropical interannual variability in the CCC is to low and in the HC it is too high [110].

A crucial unknown factor concerning future climate is the behavior of interannual and interdecadal climate patterns like PDO and ENSO in a warmer world. The simplest case would be if PDO and ENSO ceased to vary between extremes; then we could take a low-variability model like the CCC and project smooth increases in temperature and precipitation without the "noise" of ENSO and PDO. A more complex case (though perhaps no more realistic) would be if PDO and ENSO continue to behave as they have done in this century; then the changes suggested by the climate models will be modified by these observed patterns of variability, as discussed in the previous section. Years when both PDO and ENSO are in their cool phase would have higher winter streamflows than any yet observed, while years when both are in their warm phase would have lower spring and summer streamflow and snowpack than any yet observed. A more complex case would be a change in the behavior of PDO and ENSO, for instance, more frequent El Niños or more frequent reversals in the PDO. Such a change in the behavior of existing climate patterns may indeed be one manifestation of anthropogenic climate change.

The HC and CCC models yield very different behaviors of ENSO (not shown) and PDO (Figure 19). In the HC scenario, the PDO increases dramatically in amplitude; the impacts of such large swings, on timescales of a few years, could be dramatic. In the CCC scenario, the amplitude stays about the same but the mean state drifts toward a permanent warm-phase PDO. It is interesting to note that the decade of the 2090's in the HC simulation happened to have an unusually high average PDO index, contributing to the depth of the Aleutian Low shown in Figure 15. The CCC simulation also has a deep Aleutian Low during that decade, but for different reasons. These results are shown merely to illustrate the different scenarios that models currently generate for important details of future climate, like the interannual and interdecadal variability of Pacific climate.

A salient feature of Earth's past climate has been the suddenness with which climate changes can occur (like the mostly natural warming of the Earth in the 1930's). Climate models tend to underestimate the possibility of abrupt changes. Yet it is just such abrupt changes that pose the greatest challenge to adaptation.

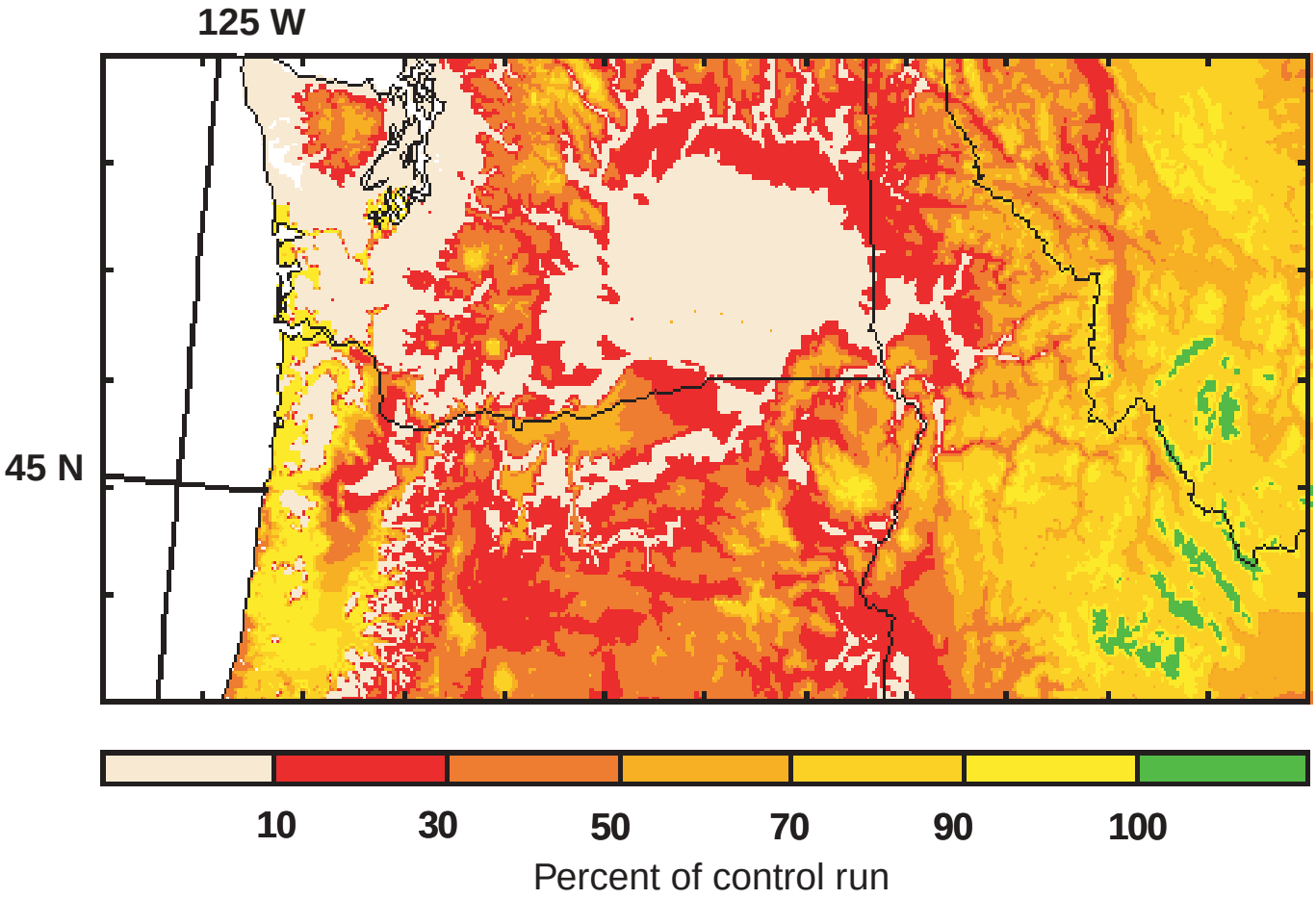

Figure 18. Mean annual snow water equivalent (swe) simulated by PNNL-RCM under $2xCO_2$, shown as a percentage of the swe in the control simulation.

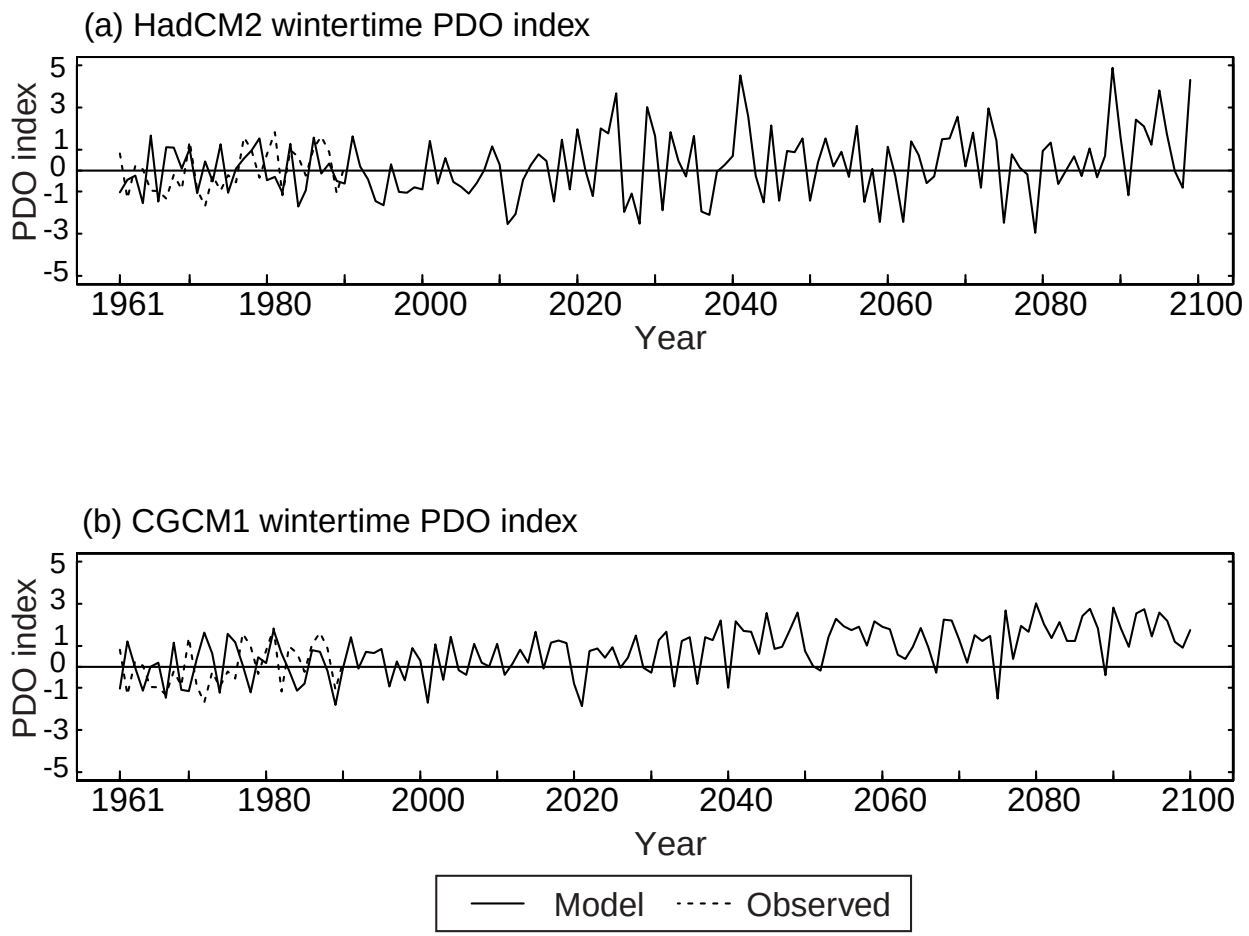

Figure 19. PDO index for the HC (top) and CCC (bottom) models from1961 to 2100.

Water Resources

Water is an extremely valuable resource in the Pacific Northwest. Much of the economic value of water stems from its abundance, yet paradoxically it is viewed in many cases as limited. An extensive infrastructure has developed around the assumption that water will be abundant year after year. For many ecosystems, availability of water is a limiting factor. Despite the reputation of the Northwest as a wet place, much of the Northwest receives less than 20" of precipitation per year (Figure 2), and the whole region experiences dry summers (Figure 3). Snowmelt transfers water from the wet season to the dry season, and from wet places (the mountains) to dry places (like the lower Columbia basin). Late in the summer there is often a low-water period after the annual snowpack has melted and before autumn rains begin.

These annual patterns of water availability, and the departures from the "usual" annual patterns, have an important impact on many human activities, especially agriculture and the production of hydropower. Consequently, this report focuses on water as a central issue.

2.1 Current status and stresses

Small changes in regional temperature, precipitation, and evaporation can cause significant changes in water supply. The amount and timing of water moving through the region is directly tied to the amount, timing, and type (rain or snow) of precipitation. **When winters are both warmer and drier than normal, snowpack and streamflow can be sharply lower than normal.**

The geographic divide of the Cascades, noted above, also partly, divides snowmelt-dominated rivers, which are mostly east of the Cascades, from rainfall-dominated and mixed rain-and-snow rivers, which are mostly west of the Cascades (Figure 20). West of the Cascade crest, temperatures in low-lying river basins are usually above freezing so most of the winter precipitation falls as rain and the rivers there have peak flows in winter. For intermediate elevation basins, the seasonal flows show the influence of several factors: precipitation falling as rain in the autumn and early winter, less runoff as winter progresses and snow accumulates, and a spring melt. Rivers in such basins have two runoff peaks, the first in mid-winter roughly coinciding with the peak of the rainfall season, and the second in late spring or early summer coinciding with the peak of snowmelt-generated runoff. East of the Cascade crest, most rivers are snowmelt-dominated rivers like the Columbia, in which very little runoff occurs during winter. Instead, accumulated winter snow melts during the spring and early summer, causing flows that typically peak in early June.

The timing and quantity of water availability, and the uses to which it is put, also vary considerably from East to West. The arid eastern part of the region, with low population but high agricultural demand, requires water resource managers to capture the rapid run-off of the snowmelt during the late spring and early summer and release it over the course of the growing season. In the western part of the region, managers for urban water supply, like their eastern counterparts, strive to ensure supply into the late summer and fall. On both sides of the Cascades, recreational users demand full reservoirs over the summer period, which conflicts with the need to withdraw water for irrigation and to maintain high flows for fish. Regional population growth (see section 1.2 of part I), as well as changing water allocation priorities, are increasingly stressing the water supply system west of the Cascades.

Water supply and water quality are currently stressed by many factors, including seasonal groundwater depletion in some areas and growing demands on surface water by

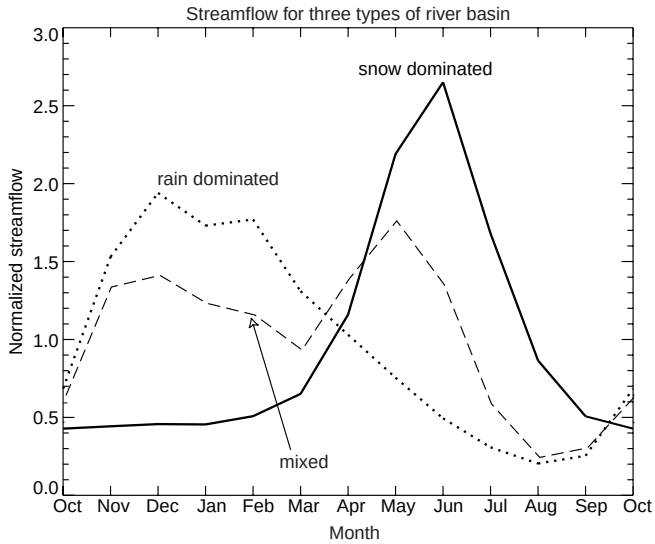

Figure 20. Average monthly streamflow for three types of river basins

a growing population. Runoff from fertilizers, herbicides, pesticides, livestock wastes, salts, and sediments reduce the quality of both surface and groundwater drinking supplies. Water temperature is also critical for the health of many aquatic ecosystems. Some studies have documented a temperature increase in the Columbia River coinciding with dam construction [134]. It has been suggested that this rise in temperature, although possibly due in part to changes in climate, is primarily due to increased residence time of water in reservoirs, changes in the timing and volume of streamflow, and changes in the level (surface or bottom) of the reservoir from which water is released.

The Columbia River basin is one of the largest in North America. It provides drainage for approximately 75% of the PNW and accounts for about 55%—65% of the total runoff from the region. The Columbia River system, with more than 250 reservoirs and 100 hydroelectric projects, is one of the most highly developed in the world with little room for future expansion or development. The system is managed for **electric power generation, flood control, fish migration, fish and wildlife habitat protection, water supply and water-quality maintenance, irrigation, navigation, and recreation** by a variety of agencies and public and private utilities. The largest share of water withdrawn from the Columbia is used for agriculture, but there is increasing demand from other human uses, particularly municipal and industrial water supply. In addition, fisheries protection is gaining importance in determining how water is managed.

A complex tangle of **international, federal, regional, state, tribal, and local entities have competing jurisdictions** over a variety of managerial aspects of the Columbia River system. Different kinds of climate variations pose different kinds of stresses on the system. When floods are an immediate threat, the U.S. Army Corps of Engineers has clear jurisdiction to ensure that releases from the dams prevent flooding on the lower Columbia. Droughts, however, expose the conflicts among various entities that assert competing claims to water. The nature of these conflicts changed in recent years when the preservation of various species of fish climbed almost to the top of the priority list, second only to flood control.

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2.2 Past changes and the impacts of climate variability

As noted in section 1.1.1, when hydrological and climatological variations are considered together, the dominant natural pattern of winter-to-winter variations is for warm winters to be relatively dry and for cold winters to be relatively wet. This pattern also characterizes the variations associated with extreme phases of both ENSO and PDO. **We have found fairly robust signals of ENSO and PDO in the region's snowpack—especially at moderate elevations—and streamflow.** At Snoqualmie Pass in Washington, elevation about 3400 feet, the depth of the seasonal snowpack is generally somewhat lower in El Niño years than in La Niña years, and the difference is even greater when the phase of the PDO is the same as the phase of ENSO (Figure 21). The difference between phases of ENSO alone does not emerge until midway through the winter accumulation period. (The differences shown are statistically significant at the 95% level except in mid-November and, for the top panel, early January to mid-February.) It also appears that the transition from snow accumulation to snowmelt may occur earlier during warm-phase years, and one may infer that a larger fraction of winter precipitation falls as rain than as snow at this elevation.

The three types of river basins illustrated in Figure 20 have similar responses to the warm-dry or cool-wet winter climate patterns. Warm-dry winters tend to

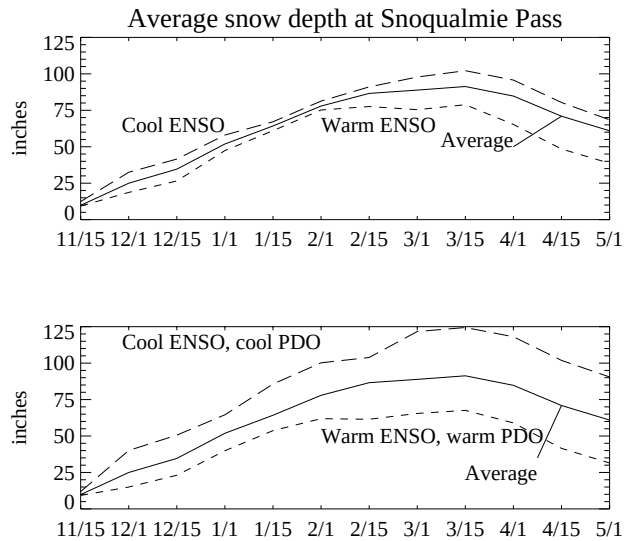

Figure 21. Average snow depth, as winter progresses, at Snoqualmie Pass, Washington, for the warm and cool phases of (top) ENSO only; (bottom) ENSO and PDO in combination.

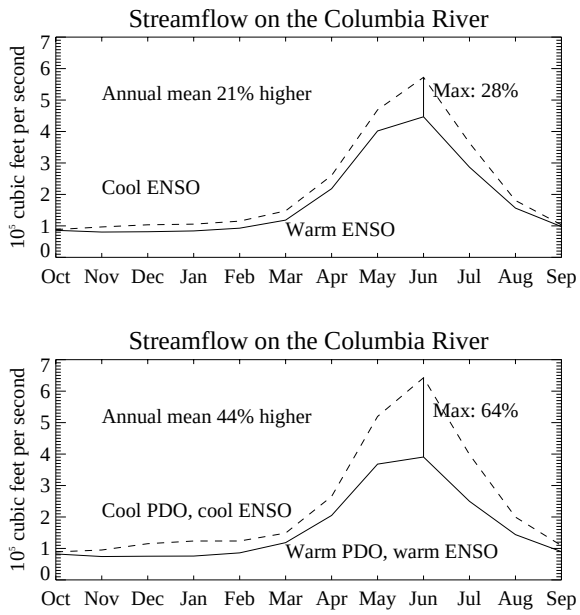

Figure 22. Monthly average streamflow (natural) on the Columbia River for the cool and warm phases of ENSO.

produce low winter runoff, low accumulations of snowpack, early spring melt, and reduced spring and summer streamflow because of decreased snowpack and increased evapotranspiration. Cool-wet winters tend to produce the opposite effects in each case.

In this section we describe quantitative links between ENSO or PDO and streamflow on various rivers. To define the state of ENSO, we use the Niño 3.4 index (see page 13) and we define an El Niño event when the December-February average of the index exceeds 0.5 standard deviations (about 0.47˚C) and define a La Niña event when the index is below 0.5 standard deviations. PDO phases are considered to be 1900—24 (cool phase), 1925—46 (warm phase), 1947—1976 (cool phase), and 1977—present.

2.2.1 Impact of PDO/ENSO on Columbia River flow

In order to study the interannual variations in Columbia River streamflow over many years, we must attempt to correct for the effects of changing diversions, storage in reservoirs, and increased evaporation (due to increased surface area). All the data shown here have had such corrections applied and will be called “natural”. The original data are from a stream gauge at The Dalles, Oregon, from 1879—1997.

Averaging the Columbia River streamflow for the warm and cool phases of ENSO (Figure 22), we find that natural streamflow tends to be higher during the cool phase of ENSO than during the warm phase, and that the largest differences occur during the peak flow months. The yearly total flow is about 20% higher during La Niña events than El Niño events.

The effect of the PDO on streamflow in the Columbia is similar to the effect of ENSO, and in general their effects are additive. The average difference in streamflow between cool and warm phases of the PDO is about 20%. Considering also the phase of the PDO, the differences are even more pronounced (Figure 22, bottom panel), as with snowpack (Figure 21). The primary reason for the sensitivity of the Columbia River to PDO and ENSO

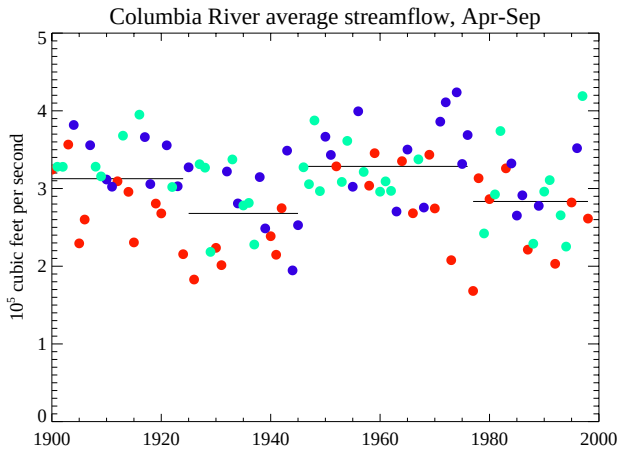

Figure 23. Summer streamflow totals for each year. The averages for alternating phases of the PDO are indicated by horizontal lines; El Niño years are shown by red dots, La Niña years by purple dots, and ENSO neutral years by blue dots.

is that the winter-season snowpack depends on the average climate over the entire basin, which in turn depends on the large-scale atmospheric circulation.

The combined influences of PDO and ENSO on year-to-year variations are evident in Figure 23. Not only do the phases of ENSO and PDO influence the mean streamflow, they also affect the likelihood of extremes; four[1] of the top five highest-flow years occurred when the PDO was in its cool phase, and three of the top five occurred when ENSO was also in its cool phase. Likewise, all five lowest-flow years occurred when the PDO was in its warm phase, and in four of those years ENSO was also in its warm phase.

The possible exception to the pattern was 1997, the second-wettest year ever; it exceeded the greatest flow for any warm-phase PDO year by such a wide margin that we wonder whether the PDO may have shifted back to the cool phase; if it has, then all five highest-flow years have occurred in the cool phase.

2.2.2 High flow and floods

Flooding is usually associated with river flow that is sufficiently large to overflow the normal river channel and inundate surrounding land. This generally occurs when the river's flow exceeds the channel capacity, or bank-full flow. For most streams, bank-full flow corresponds approximately to the mean annual flood, defined as the long-term average of the largest daily flow occurring each year. However, the atmospheric conditions leading to flooding vary greatly from one river to another and even for different locations on a river, owing to the influences of the basin's elevation and the properties of the river channel.

In snowmelt rivers, flooding is often caused by rapid warming, accompanied by intense rain on snow. This kind of flooding usually occurs in fall or winter in basins that have a transient snow zone, or in spring in snowmelt dominated systems. Flooding in rain-dominated basins is predominantly caused by extreme fall and winter precipitation events. Heavy rains falling on saturated soil for a number of days result in unusually high river flow.

The effects on any given river are also governed by the topography and human development of the basin. In parts of some river channels, low banks and low-lying areas adjacent to the channel lead to flooding for flows that are only moderately high, while in other river channels with high, steep sides, flooding only occurs with the most extreme flows. Rivers that have flood control dams have differing sensitivities to high flow, depending on the available storage and how the dams are operated.

To assess the relationship of climate variability to the likelihood and severity of flooding, we performed a pilot study using long streamflow records from five uncontrolled basins in different parts of the region (Figure 24). These basins were chosen to cover a range of hydrologic types and a number of different topographical and geographical features of the region. The Siletz is a coastal, rain-dominated basin in Oregon. The Skykomish basin, on the western slopes of the Cascades in Washington, is a transient snow basin, meaning that it is only intermittently covered with snow; it thus has mixed rain and snow characteristics. The other basins are snowmelt -dominated rivers east of the Cascades at different distances from the coast. For each basin, we considered six climate categories depending on the phases of ENSO and PDO. For each category, we calculated the probability that the year's highest daily flow exceeds the mean annual flood. For brevity we refer to this probability as the probability of flooding, and the results are shown in Table 4, ranked roughly by the magnitude of the difference in probability of flooding between the two phases of the PDO.

Figure 24. Location of stream gauges used for flood study. The Columbia basin is shaded.

PDO	warm	warm	warm	cool	cool	cool
ENSO	warm	neutral	cool	warm	neutral	cool
Flathead	0.09	0.10	0.20	0.38	0.90	0.75
Boise	0.07	0.47	0.54	0.43	0.77	0.69
Kettle	0.31	0.46	0.33	0.63	0.60	0.67
Siletz	0.36	0.33	0.42	0.13	0.60	0.58
Skykomish	0.38	0.46	0.75	0.25	0.20	0.58

Table 4. Probability of flooding in the indicated climate category for five PNW river basins.

Most of the rivers, except the Kettle, show a relationship between ENSO and the probability of flooding. The snowmelt-driven rivers (Flathead, Boise) also show a strong relationship between the PDO and probability of flooding. This is particularly true of the Flathead, where flooding is very unlikely in the warm phase of the PDO. The other basins show a weaker relationship to the PDO. In all of the rivers there is a significant difference in probability of flooding for the climate categories in which ENSO and PDO are in phase (far left and far right columns). **Warm PDO combined with El Niño is associated with a reduced likelihood of flooding, and cool PDO combined with La Niña is associated with increased likelihood of flooding.**

Differences in the characteristics of the basins help explain the relationships between the likelihood of flooding and PDO or ENSO. In rain-dominated rivers, flooding is a short-duration response to high rainfall over a short period of time, sometimes in a single storm, and usually between November and January. In snowmelt-dominated rivers, flooding usually occurs after exceptionally heavy snow years, usually between March and July. Because the snow is deposited over many months, flooding depends on the weather over the whole winter and spring. Since the season's weather is more sensitive to the state of PDO or ENSO than is a single storm, flooding in snowmelt-dominated basins is likely to be more sensitive to PDO or ENSO. It is unclear, however, why the flooding behavior of the Kettle is so different from the other snowmelt-dominated rivers.

Although the probability of flooding shows an association with ENSO and/or PDO for most of the five basins, the average *severity* of flooding (not shown) does not. It is likely, therefore, that this aspect of the response is determined more by the random character of individual weather events than by average regional and seasonal climate characteristics. This preliminary result has important implications for medium-range forecasting of high-flow events. While the probability of events above the mean annual flood can be estimated with long lead times based on ENSO forecasts and persistence of the PDO, the results show that there is little ability to predict the exact timing or relative severity of these events except on a storm-by-storm basis (i.e., with lead times of perhaps a few days, a time horizon governed by the accuracy of weather forecasts).

2.2.3 Low flow and drought

Unlike floods, droughts are characteristically long-term events. The effects of droughts are specific to particular regions and river basins, and are a complex function of climate, hydrologic response, physical characteristics of the dams and reservoirs in place (e.g., amount of storage available), uses of water in the basin, and the reservoir operating policies in place at any given time. Because of these complexities, it is unlikely that any single definition

of drought will be acceptable for every situation. For the Columbia River, the ColSim reservoir model (see Appendix C) has been used to identify a number of streamflow sequences, in the period 1931—1988, that had measurable impacts on water uses affected by low streamflow. To extend the analysis to earlier years when the detailed streamflow data needed to run the reservoir model were not available, an objective definition of drought was developed based on the drought periods identified in the ColSim model runs from 1931 to 1988. Droughts were defined using a threshold of -0.9 standard deviations below the long-term mean for the natural streamflow at a particular river point, using monthly-averaged data; droughts are those periods for which the streamflow was below the threshold for at least six months, and streamflow did not exceed the threshold for more than three months out of 12. This definition is somewhat subjective, and is completely dependent on the simulated uses of the reservoir system and its current operating policies, implying that these drought periods may not have been perceived as droughts at the time. Nonetheless, the formula is useful for defining a group of low-flow sequences that may be considered the most severe multi-year droughts in the Columbia Basin. Using this definition, the drought periods from 1900—1997 are:

1. Feb 1905—Jun 1906
2. Dec 1928—Feb 1932
3. Oct 1935—Aug 1937
4. Jan 1944—Aug 1945
5. Jun 1987—Sept 1988
6. May 1992—Oct 1995

Severe multi-season drought sequences like these for the Columbia River typically contain several winter low-flow months during which reservoir storage is depleted for winter energy generation, followed by summer low-flow conditions that prevent reservoir refill, causing in turn heavy impacts on reservoir storage in the following winter, especially if this succeeding winter is also very dry. These conditions are primarily caused by abnormally low winter precipitation, which is strongly influenced by PDO and ENSO. Five out of six events are in PDO warm epochs, four out of six events contain multiple warm ENSO events, and three out of six contain back-to-back warm ENSO events. In addition, the set of years when both ENSO and PDO are in the warm phase contains a large number of very low flow years on an annual basis, including water year 1977, which is the lowest flow on record for the Columbia Basin (Figure 23).

Figure 25. Irrigated farmland in the dry Yakima Valley. Sagebrush (foreground) emphasizes that this region is naturally a desert.

Until recently, a 42-month period from 1928—1932 was the critical period defining the minimum guaranteed hydropower that the system could deliver. Recent changes in the reservoir operating system to protect spring and summer streamflow have moved the critical period to a 9-month streamflow sequence in the period from 1936—1937. This change illustrates the kind of complex interactions between hydrologic conditions and reservoir operating practice that can occur.

2.2.4 Case study: Yakima Valley irrigated agriculture

In a recent study, Gray [52] examined the impacts of 20th century droughts on irrigated agriculture in the Yakima valley. The story is a striking example of how management practices can affect vulnerability to climate variations and climate change.

The Yakima valley is nearly the driest place in the Pacific Northwest (Figure 2), and yet because of irrigation it

contains some of the most fertile farmland in the world (Figure 25). Annual revenues from agriculture are about $2.5 billion, primarily from tree fruit (e.g., apples, cherries, and pears). Fully 80% of the farmed area of 578,000 acres is irrigated. The Yakima River basin is a strongly snowmelt-dominated system with its main storage reservoirs in the mountains; with the storage capacity in the reservoirs at about half of annual demand, the basin can tolerate a moderate single-year reduction in streamflow. Most farmers also have their own wells and can pump groundwater in times of low flow.

Several aspects of water management have increased the vulnerability to drought [52]. First, water rights in the Yakima basin, as in much of eastern Washington, are divided by law among "senior" users and "junior" users. Senior users are essentially guaranteed their full allocation every year, whereas junior users are not; in years with insufficient water to meet demand, it is the junior users who suffer, losing as much as 63% (in 1994) of their allocated water, with attendant economic losses of about $140 million [111]. This system of water rights has created the incentive for junior users to "cheat" by drilling illegal wells to minimize damage to crops during drought years. This practice is depleting the groundwater source and perpetuating the myth that enough water exists in the Yakima Valley for all. Second, there is no coherent basin-wide strategy for dealing with drought. Third, gains in efficiency and in conservation have increased vulnerability to drought. Farmers once allowed much of their allocation to flow through the orchards or fields and back into the river, with the result that water could be re-used. Such habitual waste left some wiggle room for drought years. But now, increased efficiency has reduced the re-use of water and increased vulnerability.

Another important factor that has contributed to the vulnerability is that annual crops (those that must be replanted every year) have slowly been replaced by more lucrative perennials (primarily tree fruit, but also grapes and hops). Annuals provide more year-to-year flexibility, require less water, and are of lower dollar value, whereas high-value perennials that took, say, 7 years to generate any revenue can be destroyed in a single year. Farmers growing perennials (at least those in junior districts) face potentially greater losses and have fewer options for dealing with drought.

The PDO clearly plays a role in the occurrence of drought in the Yakima Valley and in the expectations of agribusiness. Junior users have suffered reductions in water supply eight times since 1945, all but one (1973) in the warm phase of the PDO. Significantly, the expansion of the agricultural industry in the Valley has also followed the PDO cycle, with expansion during the previous cool phase (1945—1976) but no significant contraction after 1977. Instead, the cool phase created expectations of abundant water, which have repeatedly gone unfulfilled in the latest warm phase. Even the enactment of new water regulations (generally in response to droughts) have followed the PDO cycle. Regulations began with a major decision in 1945 at the end of the previous warm phase, but there were no new regulations at all during the cool phase, then a spate of regulations after 1979 in response to more frequent droughts in the warm phase of the PDO.

2.3 Possible future changes and the impacts of climate change

To evaluate the potential impacts of climate change on the water resources of the PNW, we use a detailed hydrology model (VIC) for the Columbia River basin combined with a model that incorporates current operating rules (ColSim). These two models, which are described in Appendix C, provide a comprehensive view of both the natural and the managed response to climate change. An expanded analysis can be found in Hamlet and Lettenmaier [60].

The horizontal resolution in the global climate models is still insufficient to resolve mountain ranges whose horizontal extent is smaller than the Rockies. For this reason, climate models are not suitable by themselves for evaluating hydrological changes at the regional scale. Important features may be missing entirely, like the difference in climate between the west and east sides of the Cascades. To translate climate model output to the regional Scale, a range of approaches are possible, from the most qualitative to the most detailed. First, one can qualitatively examine the climate model output and seek to understand why the changes happen, then attempt to apply that understanding to the region's actual climate. For instance, projected changes in winter precipitation over the PNW are associated with changes in the storm track and the surface pressure distribution (see Figure 15), which would in turn give southwest-facing river basins a greater increase in precipitation than northwest-facing basins. Second, one can downscale the climate model

output using a variety of empirical techniques for quantitative results. Third, one can run a regional climate model which combines circulation patterns from the global climate model with the regional landscape. Important features like the Cascades can then be included.

We first downscale the results to a finer grid by applying the area-averaged change in temperature and area-total change in precipitation calculated by the climate models to the present fine-scale distribution of temperature and precipitation, using the VIC hydrology model (see Appendix C). In this way we obtain results with the spatial complexity of observed data and the gross decade-to-decade changes from the climate models.

Figure 26 shows maps of snow cover calculated with the VIC model for baseline climate conditions and for climate-change scenarios generated by the Hadley Centre model. Because this is a river-basin model, snow cover outside the Columbia basin is not shown. As the climate warms, low-elevation areas lose their snow first, and the most obvious changes in area covered by snow are in the lower part of the Columbia basin. The deep snow in the upper part of the basin (the Canadian Rockies) remains on the ground late in the season even for much warmer climates, in contrast with the dire result mentioned on page 23 (the complete disappearance of snow from the PNW in the coarse-resolution CCC climate model).

We have also used the VIC hydrology model to quantify the impacts of climate changes on the Columbia River. All of the climate model scenarios lead to increases in winter streamflow and decreases in summer streamflow (except for the 2020s in the HC simulation, which happened to be a wet decade compared to most other decades of the 21st century); the peak flow tends to shift about one month earlier in the year (Figure 27). The winter increases occur because of increased precipitation and because higher temperatures raise the snow level so that more precipitation falls as rain and is not stored as snow. The summer decreases occur largely because of higher temperatures, which increase evapotranspiration, decrease spring snowpack, and cause snow to melt earlier.

Annual runoff volume may increase or decrease depending on the relative weight of the winter increases and the summer decreases. The net effect for the 2020s ranges from a reduction in annual flow volume of about 6% for the GFDL model to an increase of 22% for the HC model. For the 2050s, the net effect ranges from a decrease

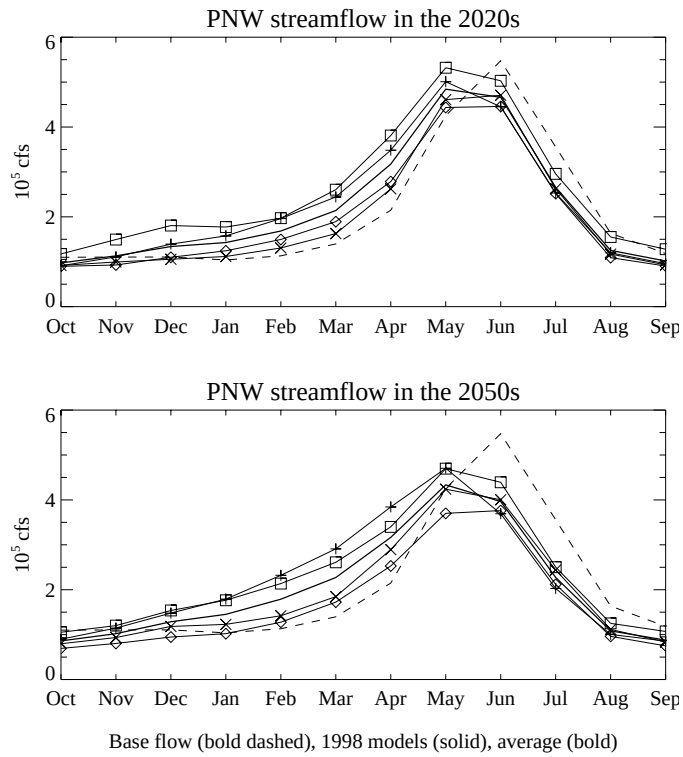

Figure 27. Projections of climate-related change in streamflow for the Columbia River using climate scenarios from the CCC (+), HC (boxes), GFDL (x), and MPI (diamonds) models for the indicated decades. The bold curve shows the average of the four scenarios and the dashed curve shows the base case (pre-industrial).

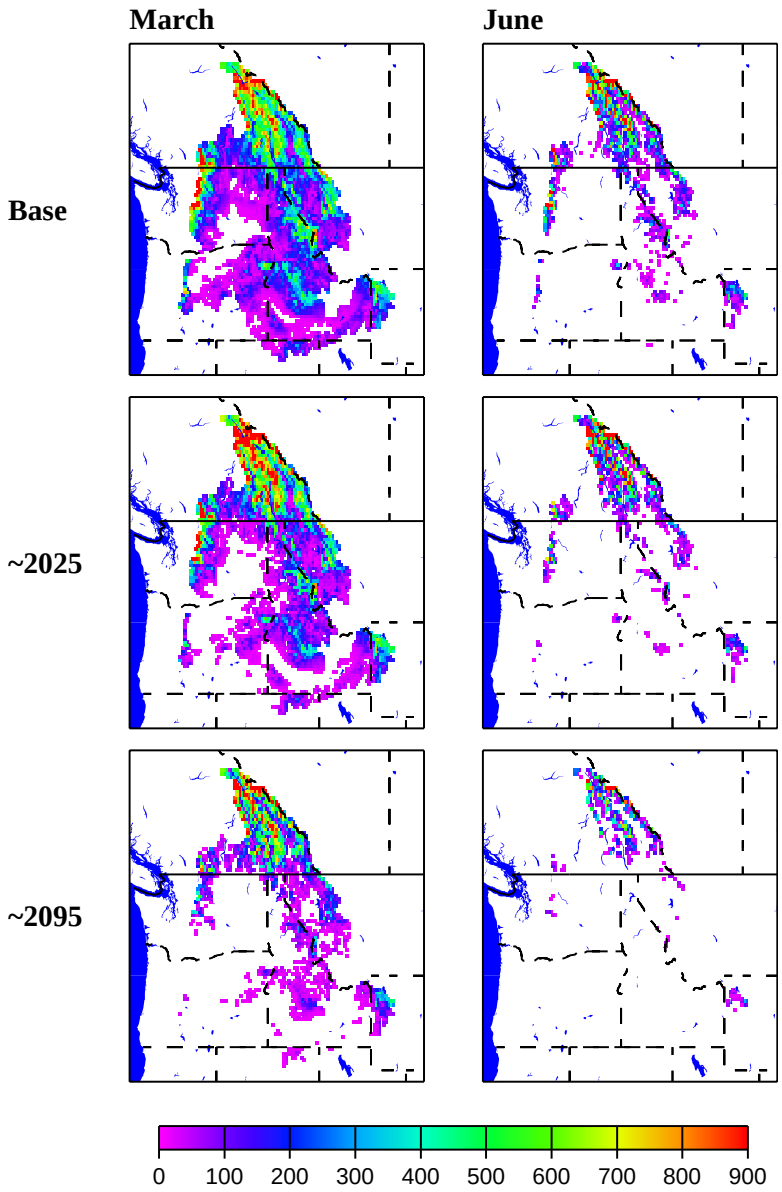

Figure 26. Average March 1 and June 1 snow water equivalent (mm) simulated by the VIC hydrology model for the Columbia River Basin for the base case (pre-industrial CO_2) climate and for the climate in future decades centered on 2025 and 2095, where the climate of the HC model is used. Snow outside the basin is not indicated.

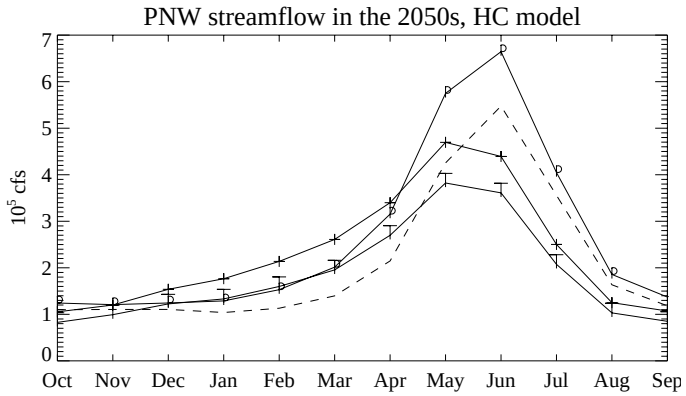

Figure 28. Changes in Columbia River flow under the Hadley Centre model scenario considering the separate influences of changes in temperature (T) and precipitation (p).

of 19% for the MPI model to an increase of 10% for the HC model. While the changes in annual volume do not even have the same sign for all the models, the large increases in winter flow and decreases in summer flow (which the models fairly consistently suggest) could have dramatic consequences, as will be discussed shortly.

Projections of temperature changes, both globally and regionally, are made with higher confidence than precipitation changes, as illustrated by the spread of results for the different models shown in Figures 13 and 14. It would be useful to know the degree to which our results depend on the precipitation changes, which are less certain. To elucidate the separate roles of changes in temperature and precipitation in altering the region's hydrology, we have run the hydrology model using climate changes for the 2050s from the HC model and holding one variable fixed while changing the other (Figure 28). If precipitation changes but temperatures remain as observed, increases in the flow occur in all months but the timing of the peak flow does not change. If temperatures change but precipitation remains as observed, winter flows increase moderately owing to the greater fraction of precipitation falling as rain, and summer flows decrease substantially because of reduced snowpack, an earlier melt season, and higher spring and summer evapotranspiration. Thus it is clear that temperature changes alone, which we can project with greater confidence than precipitation changes, have a substantial impact on summer streamflow.

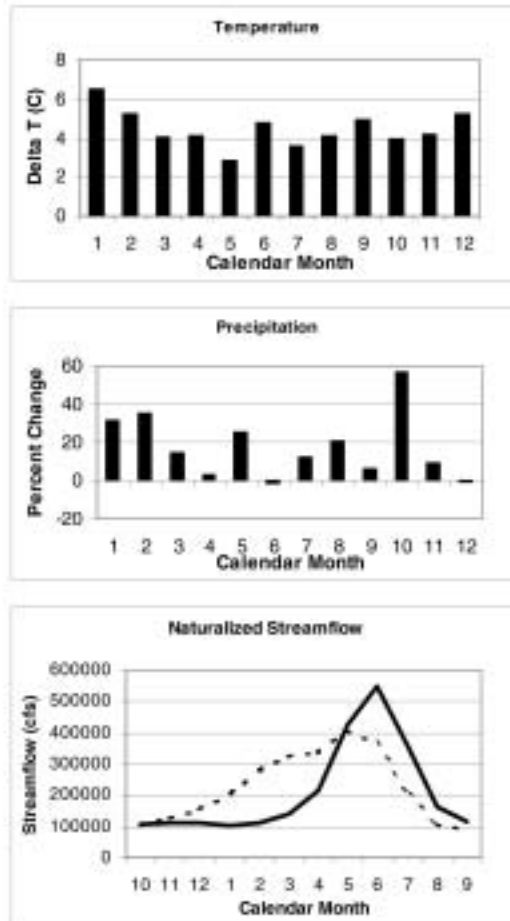

Figure 29. Streamflow, precipitation, and temperature changes for the 2090's from the HC model. In the bottom panel, base-case streamflow is solid and 2090s streamflow is dashed.

For the longer time horizon of the 2090's, for which we have analyzed only the HC model output, we find temperature increases of about 7˚F and a nearly year-round increase in precipitation. The combination of these effects leads to a large reduction in summer streamflow and a large increase (more than double) in winter streamflow (Figure 29). Even with these drastic changes, the peak streamflow only shifts one month earlier. The hydrological changes are clearly linked to the changes in snow cover (Figure 26).

In order to give a smaller-scale perspective on these hydrological changes, we describe work done at PNNL (see section 1.2.4), where researchers have used their regional climate scenarios to drive a distributed hydrology model over two mountain watersheds to evaluate the impacts of climate change on hydrology over the PNW. Biases are removed from both the control and climate change simulations based on the regional mean differences between the control simulation and observations. The American River watershed is located on the east of the Cascades near Mt. Rainier. The Middle Fork Flathead watershed is located in the Northern Rockies of Montana. Both watersheds are snowmelt-dominated, although the American River watershed is warmer and therefore closer to snowline. As shown in Figure 30, over the American River watershed, snowpack is reduced by about 50% and there is a significant shift in the timing of runoff under the climate change conditions suggesting a higher likelihood of wintertime flooding and reduced water supply during the warm season. Over the Middle Fork Flathead the change is much less drastic because wintertime temperature is so low, even under the PNNL climate change scenario, that snowpack is only reduced by about 10% and the seasonal pattern of streamflow remains intact.

In summary, **warming will generally reduce snow cover, which in turn will have profound impacts on the streamflow** characteristics for the three types of river basins. Some snowmelt-dominated basins could shift toward a mixed regime (as our modeling results showed for the Columbia and the American Rivers). Rainfall-dominated rivers (i.e., low-lying basins west of the Cascades) would probably experience greater winter flow volumes and a higher likelihood of flooding under any of the climate model scenarios. Rivers with both rainfall and snowmelt responses would probably also see an increase in winter flow volumes because of higher temperatures. These fundamental changes in the hydrographs of rivers will have enormous consequences and could eventually change how the rivers are managed.

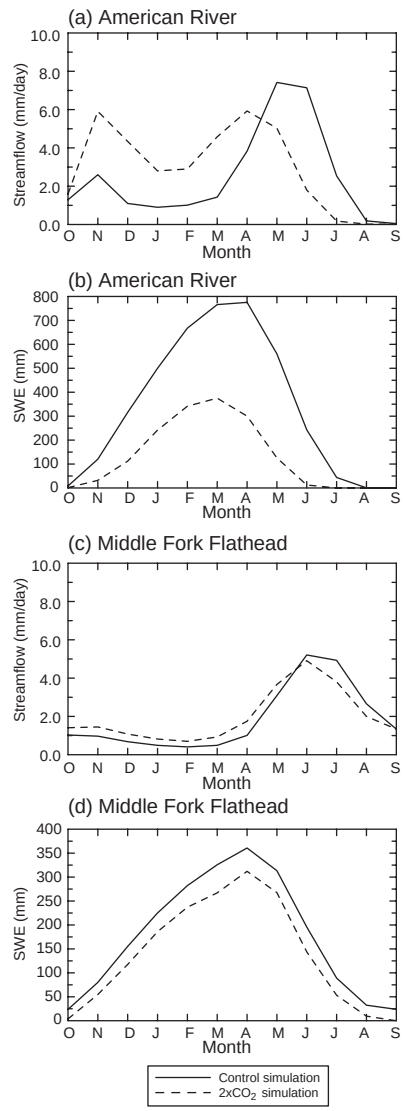

Figure 30. Control and 2xCO_2 simulations of streamflow and snow water equivalent in the American River in Washington and the Middle Fork Flathead River in Montana.

2.4 Socioeconomic impacts of the likely changes

As was outlined in section 2.1, the system for managing water resources in much of the PNW is fairly effective at dealing with high flows, but low flows expose the system's weaknesses. The climate change scenarios discussed above suggest that once anthropogenic climate change emerges above

the "noise" of natural interannual variability, the changes in temperature and precipitation will be in the "wrong" direction, toward lower flow in summer, compounding the conflicts generated by other factors such s the rapidly growing population and the recent requirements to maintain minimum flows for fish. In this section we explore in more detail some of the possible socioeconomic impacts of projected climate-induced changes in water resources. **These impacts are strongly influenced by the way in which human institutions have been designed.** In some instances, management structures incorporate climate information, though seldom as fully as they could; in others, climate information appears to have been ignored.

As an example, the "rule curves" governing how reservoir levels are managed between August and December are designed on the basis of a "critical period" of low flow, the lowest flow period of the century (1936—37) in the case of the Columbia. These rule curves provide guidance on maintaining reservoir levels in order to prevent flooding and are based upon observed flow variations in the past. The impacts of climate variability and change are inseparable from the reservoir operating procedures, because the rule curves implicitly assume that climate is unchanging; hence, actual reservoir levels are a function both of hydrological conditions and of the rule curves which assume that variations will fall within the past range. If a drought worse than the current critical period were to occur, the resultant conflicts and the failures to meet various demands would probably lead to changes in the operating rules, particularly with regard to firm energy production. Changes in the timing of runoff (like those shown in the previous section for the Columbia and American Rivers) may require reservoir managers to rewrite the flood-control rule curves. However, barring changes in the way climate information is incorporated in management decisions (as discussed below), it could be years or even decades before climate-induced changes in the hydrograph of a river lead to the revision of the rule curves.

To a large extent, **the socioeconomic impacts of climate-induced changes in the region's water resources will stem from the change in timing and volume of streamflow in the snowmelt-dominated rivers,** combined with climate-induced changes in demand. For example, seasonally varying demand for hydropower has two peaks: winter, for local heating, and summer, for cooling (primarily outside the PNW). On one hand, if climate change decreases the summer flow and at the same time rising temperatures increase the local and distant demand for electricity, then the price of summer hydropower could rise substantially. On the other hand, the price of winter hydropower could drop as supply increases and demand decreases (due to lower demand for heating). The deregulation of the electric utilities vastly complicates any analysis of the possible future economic impacts of climate change on hydropower, because we know very little about how the markets will operate in the future and about how they will respond to stresses such as climate variability and change.

2.4.1 Management of water resources in the Columbia Basin

While there is considerable diversity in PNW water resources systems, our study has focused almost entirely on the Columbia River Basin. There are two primary reasons for this choice. First, the Columbia basin is so large that it averages the weather conditions over large space scales and long times, whereas smaller basins reflect local effects. Second, the Columbia is the primary regional source of energy and irrigation water, both of which are crucial to the PNW regional economy. The Columbia basin is also an important ecological and cultural entity in the PNW. These aspects of the basin are perhaps most evident in the struggle to preserve the endangered salmon fisheries in the river, which may have limited economic value, but are of considerable cultural and political importance to many people in the region.

There are two primary planning periods used for management in the operational water year in the Columbia Basin, which runs from August to July. In the "fixed" period from August through December (Figure 31a), operations are guided by critical period analysis and are essentially unaffected by any forecast information. Fixed rule curves are designed to provide adequate flood storage and restrict hydropower operation to help ensure a high probability of reservoir refill by July 31 and to prevent early season use of storage that may threaten late season hydropower production. In the variable period from January to July (Figure 31b), reservoir operations are guided both by critical period analysis and forecasts of spring runoff based on measurements of snow pack. These forecasts are used to create rule curves for hydropower and flood control that are responsive to conditions in the basin in the current water year.

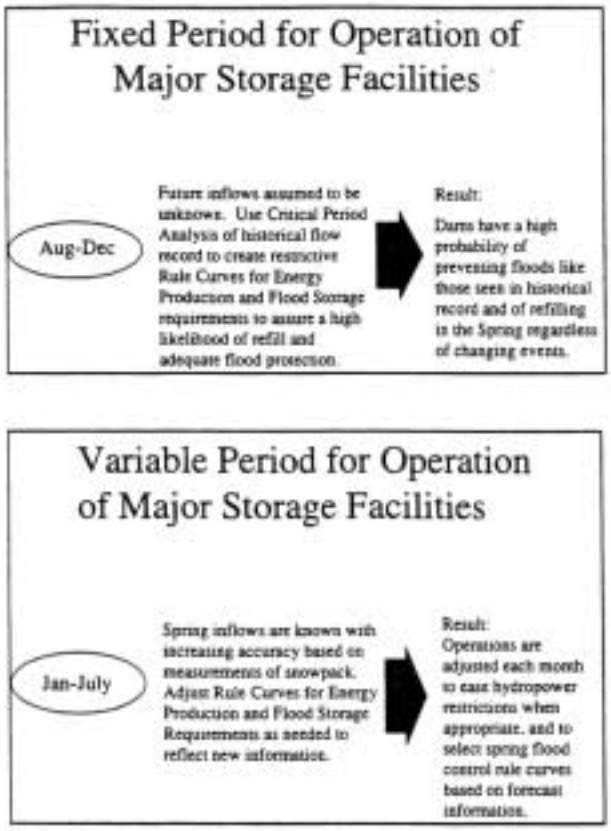

Figure 31. Operational planning periods for the Columbia Basin.

2.4.2 Water resources objectives

Because the Columbia River system is so highly managed, and because so many uses depend on water in the river, the "natural" flow simulated by a hydrology model is inadequate to evaluate the availability of water in the Columbia for human needs. To address this deficiency, the ColSim reservoir model (see [105] and Appendix C) incorporates both physical inputs (streamflow over the course of a year, which depends on the year's weather) and the system's actual operating priorities and demands, and allows the evaluation of the "reliability" of various water resource objectives under the given climate conditions. In short, the ColSim model provides estimates of how reliability depends on climate. Reliability is defined as the observed probability of meeting a particular objective. For example, an objective with 90% reliability will be met 90% of the time. The full list of objectives is given in section 2.1; two examples are the two basic types of energy contracts that hydropower companies make with their customers: to provide firm or non-firm energy. Firm energy is based on long-term contracts and is provided at higher cost but is virtually guaranteed; it is based on the hydropower capability defined by a critical low-flow sequence (currently 1936—37). Non-firm energy is often based on short-term contracts, is provided at lower cost, and is less reliable because it depends on the uncertain surplus flow in spring. Firm energy production is largely limited by winter streamflow.

We look first at how reliability depends on the phases of PDO and ENSO and on two operating systems, the status quo (Figure 32a on page 41) and a hypothetical fish flow protection alternative (Figure 32b) [60]. The alternative operating system is different from the status quo in that the foremost priority of water storage is to meet the fish flow targets, whereas in the status quo there is limited storage at a few reservoirs allocated for this purpose. Note that for the status quo, firm energy production is essentially isolated from climate variability, with other uses that depend on summer streamflow typically declining in reliability in dry conditions (warm phases of PDO and ENSO) and increasing in reliability in wet conditions (cold phases of PDO and ENSO). For the alternative fish-protection operating system (not shown), the fish-flow target at McNary Dam (just downstream of the confluence of the Columbia and the Snake) is made almost 100% reliable, and other uses (including current levels of firm energy production, which are 100% reliable) become more sensitive to climate than in the status-quo. Monthly-timestep flood control (which is significant in the Columbia Basin) and navigation are largely unaffected by the choice of operating system, and both tend to be more reliable in dry conditions, and less reliable in wet conditions. Changes in reliability are not great in each case, showing that these particular objectives in the system are largely isolated from climate variability for both operating systems.

To highlight further the dependence of system objectives on climate, we performed a simple threshold analysis [105]. This approach measures how far the flow has to deviate from the mean before the objective cannot

Objective	Priority
Flood control	1
Firm energy production	1
Non-firm energy	2
Irrigation (Snake R)	2
Recreation (Lk Roosevelt)	3
Fish flow (McNary Dam)	3

Table 5. Approximate operational priorities for Columbia Basin water resources objectives.

		2020s		2090s
Objective	base case	HC	MPI	HC
Flood control	98	92	96	93
Firm energy	100	100	98	99
Non-firm energy	94	98	87	90
Snake R irrigation	81	88	76	75
Lk Roos. recreation	90	88	79	78
McNary fish flow	84	85	79	75

Table 6. Reliability of various objectives for the 2020s (from HC and MPI) and 2090s (from HC).

be met, using the standard deviation (σ) as a metric. Firm energy production and fish-flow targets at Priest Rapids and Columbia Falls are 100% reliable. For other uses impacted by low-flow conditions, we identified the following thresholds corresponding to 85% reliability (arranged in order of increasing sensitivity): non-firm energy (at -1.5σ), middle Snake River irrigation (-1.75σ), Lake Roosevelt Recreation (-0.25σ), and McNary Flow Target (-0.25 σ). For uses impacted by high flow conditions, navigation (threshold at 0.25σ) is of lower priority than flood control at The Dalles (threshold at 1.75σ). Table 5 shows the approximate operational priority based on the threshold analysis.

It should be noted that the effective performance of the operating system is not optimal and does not necessarily reflect official policy regarding the priority of different uses. For example, hydropower production and fisheries are of equal priority under the law (the Northwest Power Planning Act), but it is apparent that this has not been realized as an operational objective, despite recent changes in the operating system designed to protect spring and summer flows for salmon. This is primarily because there is very limited storage allocated to augment fish flows under the current operating system.

We now consider how reliability of system objectives could change as climate changes. The 1998 climate model scenarios were used to drive the VIC and ColSim models. Results for the 2020s and 2090s, from [60] are shown in Figure 33 on page 42 and Table 6 for the HC and MPI models, which bracket the range of results for the various models (HC is generally the wettest, MPI the driest; see Table 3).

In most of the model scenarios (including the others, which are not shown here), increases in winter flow help assure that firm energy is essentially unchanged from the base case. Some objectives (non-firm energy, irrigation) have higher reliability during the wet decade of the 2020s for the HC simulation. (As noted before, the decade of the 2020s was unusually wet in the HC simulation, so presumably he result of increased reliability shown here for the 2020s does not apply to other decades in the 21st century HC simulation.)

To put these changes in perspective, consider the impacts of ENSO and PDO on reliability of energy production (see Figure 32 on page 41). On average, the difference in reliability of non-firm energy between the warm and cool phases of PDO is about 7%. The difference between warm and cool phases of ENSO is only 2%. Other changes, though, could overwhelm these climate variations: the reliability of current levels of *firm* energy production would drop nearly 10% if management practices were modified to use all available storage to protect major fisheries flow targets. This drop would be greatest (nearly 17%) for the warm phase of the PDO.

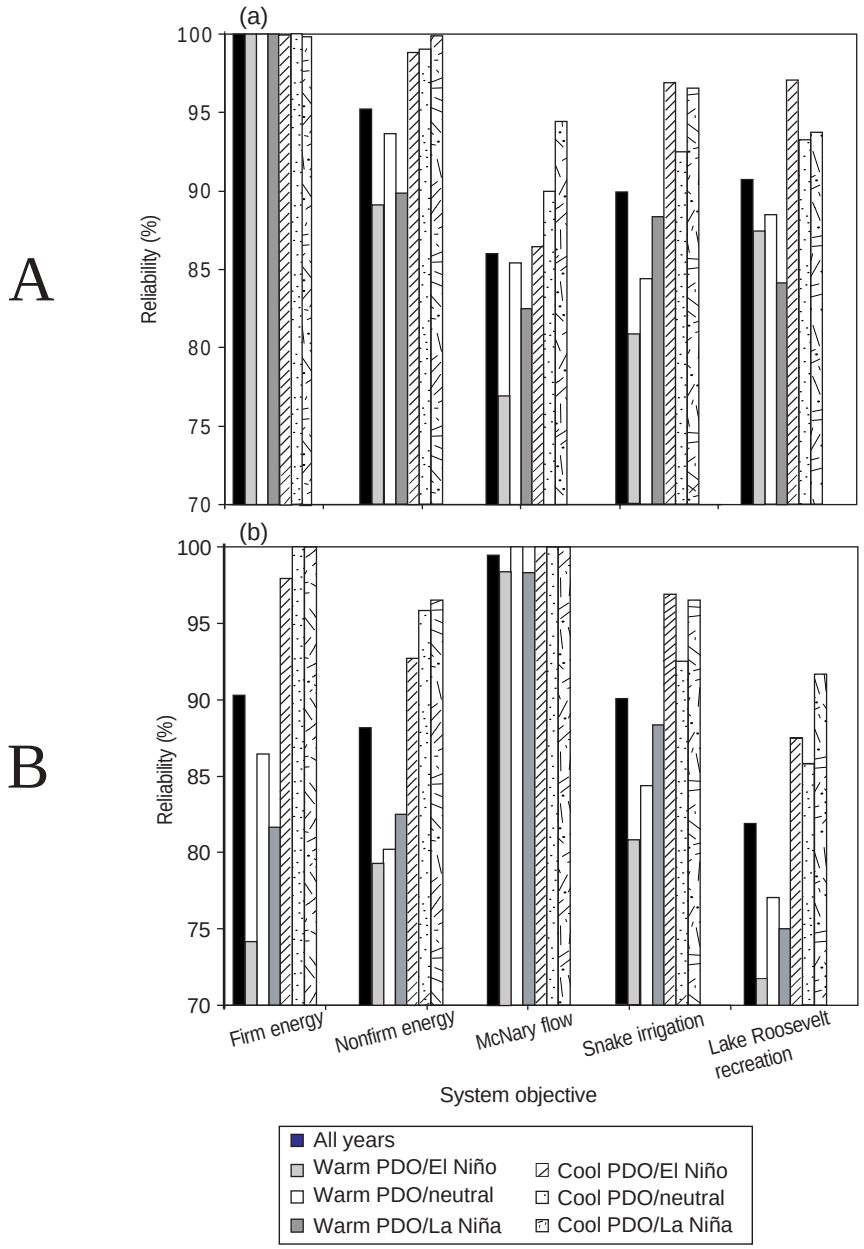

Figure 32. Reliability of Columbia Basin water resources objectives for different climate categories. Panel *a* shows the reliability under the "status quo" operating system, and panel *b* shows the reliability under the "fish protection" alternative operating system.

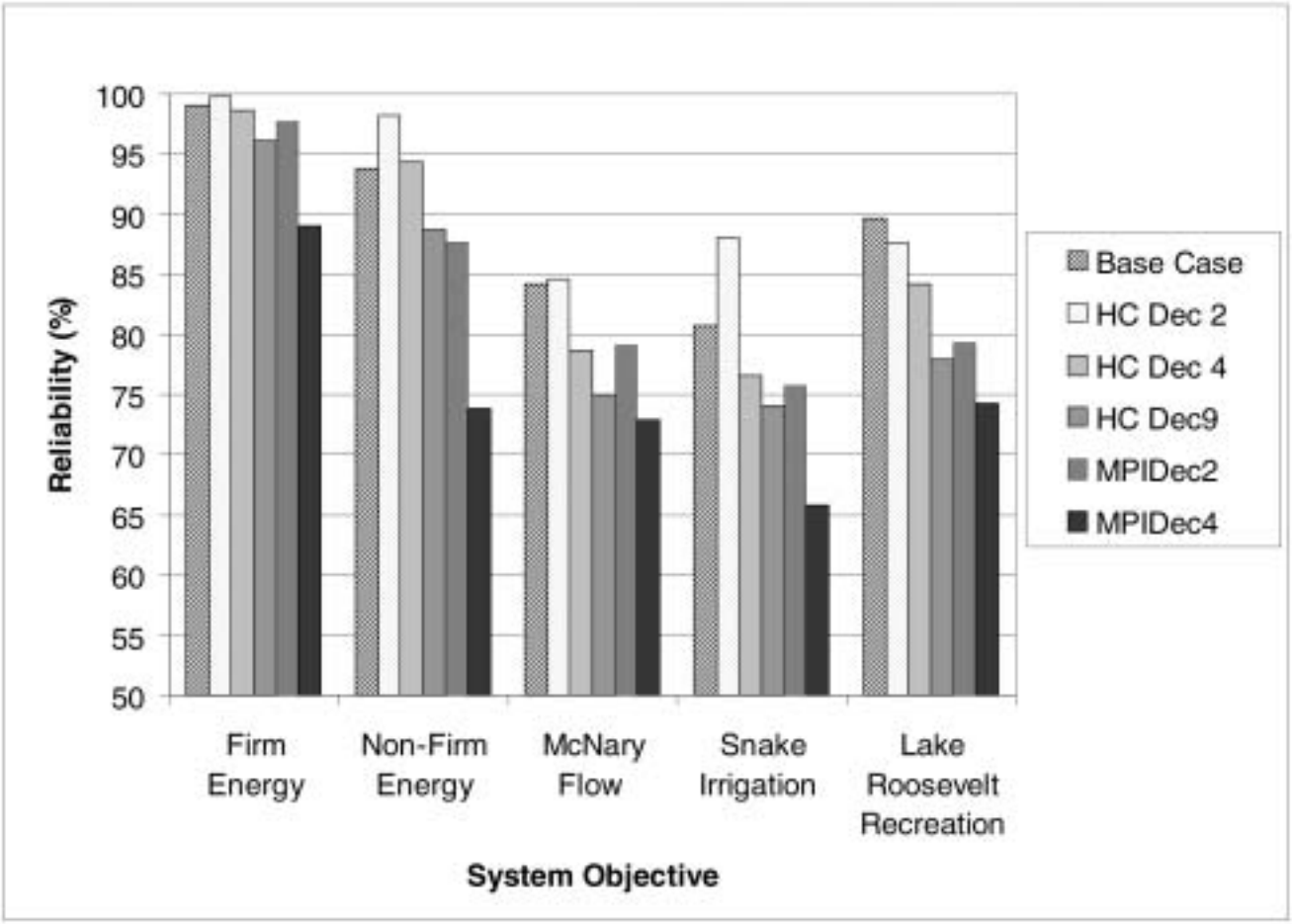

Figure 33. Reliability of Columbia Basin water resources objectives for the status quo for different climate-change scenarios.

2.4.3 Case study: Demand for water in Portland

One of the greatest challenges for PNW water districts is supplying water during the typically dry summer months. Not only does the supply decrease, but demand increases. This section describes a quantitative analysis of changes in demand in the urban area of Portland, Oregon. The results are generally applicable to most of the Northwest's cities.

The City of Portland's Bureau of Water Works is a local government utility which provides retail and wholesale water services to nearly 800,000 city and suburban customers in metropolitan Portland. The primary water source for the system is the Bull Run watershed. Two impoundment reservoirs with a storage capacity of 10.2 billion gallons and available streamflow of approximately the same amount provide a combined capacity within the watershed of about 20 billion gallons. Water is delivered to in-town reservoirs through three gravity-flow conduits. The City system can also be augmented with supply from the Columbia South Shore Wellfield, an aquifer with a nominal capacity of approximately 35 million gallons per day. A few major commercial/industrial retail customers augment local water supplies with well water; some suburban (wholesale) customers rely totally on the City for water supply, while others receive water from other sources.

The Bureau has developed an econometric model to aid in estimating near- and long-term water demands. (For details, see Appendix C.3.) The model establishes the relationship between the total water demand and selected economic and demographic variables in combination with variables representing weather and the normal seasonal cycle of demand. The model can be used to analyze the effect of economic and demographic factors like price, income, employment, and population growth on demand for water. The seasonal and weather variables in the model identify the time and magnitude of peak usage relative to the base demand.

The model can be used as a forecasting tool also. However, this requires coinciding projections of the economic and demographic explanatory variables. A demand forecast for a particular year can be estimated by using forecasts of population and other economic variables, along with the predetermined values of the seasonal variables.

This forecasting process occurs, conceptually, in two steps:

	low	medium	high
season total	27,980	28,850	30,610
daily average	229	236	251
peak day	304	355	356
Δ total	1222	1658	2323
Δ daily average	10.0	13.6	19.0
Δ peak-day	15.4	23.9	31.6
% increase in total	5%	6%	8%
% increase in peak-day	5%	6%	10%

Table 7. Impact of climate change on demand for water in Portland (in millions of gallons) during the peak season (June-September).

1. Projected economic and population variables, along with average weather for the 1940—1998 period, are used to produce a demand forecast that varies smoothly with the day of the year;

2. The impact of a particular weather year is estimated by applying the "weather effect" of a specific year (i.e., a given year's specific temperature and rainfall observations) to the smooth demand forecast.

For example, a forecast for 2050 would employ regional projections of employment and population for that year. The estimates can be further tailored to reflect the influence of a particular weather year, for instance 1991, by applying the observed weather pattern from the selected year to the projection. The resulting estimate is one which combines the influence of population on expected demand in 2050 with the peaking (i.e., weather-induced) characteristics of 1991.

In order to gauge the effects of long-term climate changes on demand, we choose representative weather years that bracket the average changes postulated by the models. Note that these years are not extremes; they do not lie outside the 2-sigma ellipse in the Portland-area equivalent of Figure 5. Instead, they are intended to represent the range of *average* conditions of the 2050s from the various model scenarios; single years would have considerably higher or lower demand than the averages reported here.

With low, medium, and high changes in the climate and weather variables determined as described in Appendix C.3, we ran the econometric model to produce demand forecasts for 2050; the results are summarized in Table 7. Changes in average

peak season demand for the 2050s affect the Bureau's ability to meet water supply needs over the entire summer season. Peak day demands, on the other hand, are more directly related to transmission capabilities and getting the water from storage to the customer. The results of this analysis indicate increases in both peak season and peak day demands: from 5% to 8% for peak season demand and from 5% to 10% for peak day demand. These changes, though much smaller than those related to population growth (nearly 50%), could increase the requirements by 10 to 19 million gallons per day to meet average daily demand, and 15 to 31.5 million gallons per day to meet peak-day demands during the summer season. These are significant quantities of water. Again, these scenarios were derived from decadal average conditions for the climate models; some years would have considerably higher or lower demand.

Although dealing with these types of incremental changes could be accommodated in the long-range planning for new facilities, it is significant to note that climate change has not heretofore been considered in the analysis of water supply requirements. The potential for decreased summer streamflows as a result of a warmer climate, in combination with existing reservoir capacity and the likelihood of climate-induced increases in demand, suggests that the impacts of climate on water resources is an area that warrants further study. An integrated approach to analyze the impacts on supply and demand of climate variability and change, along with the impacts of population growth, would be beneficial to long-term planning. Were changes of the extent described here to materialize, without proper anticipation and augmentation of water supply capability, there would likely be substantial adverse effects within the Portland metropolitan area.

2.5 Coping options for resource managers

Even if future climate were not expected to change, the region would still encounter severe difficulty during the next century as a result of the rapidly growing demand for water, which in turn is a result of projected rapid population growth (see Introduction) and other changes (e.g., expansion of irrigated farmland). The growth of demand—quite apart from any reduction in supply—implies bitter conflicts among various users of water, including irrigated agriculture, fish protection, municipal and industrial supply, and hydropower. Now, add to these stresses those generated by climate change. Warmer, wetter winters and hotter summers will reduce winter snowpack, increase winter runoff and flooding, change the spring freshet for migrating juvenile salmon, and reduce summer water supply and water quality.

We have emphasized above (see also [105]) that the region's water resources are sensitive to climate variability and change, and the institutions that manage water resources are generally less adaptable (and therefore more vulnerable) to droughts than to floods. This asymmetry in sensitivity, vulnerability, and adaptability occurs because on the high-flow side, technical infrastructure and the allocation of authority are largely adequate to the challenge, at least up to some threshold of streamflow [105, 60]. With respect to droughts, however, the only general regional mechanism for allocating water on the basis of defined priorities is the Pacific Northwest Coordinating Agreement (PNCA). The PNCA is a weak (not least because Idaho is not a member) and fragmented institution involving more than 100 parties with no one clearly in charge. Consequently, any changes to system-wide operations require heroic efforts to navigate the various bureaucracies. Because the system cannot simultaneously satisfy all demands, such system-wide changes imply winners and losers. In the face of this hurdle, only short-term incremental improvements are likely. Such improvements are not likely to provide effective responses to changes of the sort indicated by the models, or, for that matter, of the sort brought by increasing demands due to population growth.

The fact is that **from a hydrological point of view, no one speaks for the region as a whole**. There are only intricate combinations of conflicting interests, conflicting usually over the issue of whether to "spill or fill" the reservoirs [20]. Moreover, severe institutional constraints arise out of Western water law, which is based on the "Prior Appropriation" doctrine, i.e., "first in use, first in rights." This law was conceived in the late 19th century when water supply seemed inexhaustible and very few demands were being made on the rivers. Constructed with such assumptions, it cannot possibly optimize use of water at the end of the 20th century (when demand already strains supply) let alone in the 21st century, when even the lowest population growth projection for the region calls for a 50% increase by 2050 (Figure 4).

What then can we do to increase adaptability to climate change? Because there is still time to develop the

regional adaptive capacity we focus primarily on *ex ante* strategies [113] which we define as including

1. **reducing demand**, e.g., by increasing the efficiency of water use

2. **increasing the aggregate supply** of water; and

3. facilitating **institutional flexibility** by clarifying how organizational units relate to each other, who is in charge over what domain of space and issues, matching the decision rules to changed historical conditions, providing the technical infrastructure for making better decisions, and increasing regional problem-solving capacity.

In elaborating these strategies, we think they are likely to prove most effective when the Federal Government works in a long-term partnership with states to provide the technical assistance, education, and incentives to reduce vulnerabilities to the environmental security of the United States. Note that these would be federally provided services, not federal intrusion into regional authority. These services would be best coordinated by an organized **National Climate Service**. In addition, because substantial uncertainty is attached to the model scenarios of future climate change, these are all "no regrets" strategies, in the sense that they would produce major benefits to the region even if the climate either does not change or does not change as much as predicted. They are "*ex ante*" because they need to be evaluated, planned for, designed, and implemented substantially before the impacts of climate change are evident.

2.5.1 Strategies for reducing demand

At present, the Prior Appropriation doctrine prevents any semblance of market forces from applying to water use. In the Columbia Basin, senior water rights holders get water virtually for free and have little incentive for conservation, while junior water rights holders sometimes cannot get as much water as they need. This situation does not encourage conservation. Clearly, a prime strategy for reducing demand is the introduction of water markets, thereby letting the price of water accurately reflect demand and supply, and therefore scarcity. Price would then dictate the trade-offs among the major conflicting uses.

Several major problems would have to be overcome, and the scope and magnitude of these problems demand that the idea of water markets be evaluated carefully and in detail. One problem would be determining whether such a large-scale shift constituted a "taking", requiring that huge compensation be paid to senior water rights holders. Also, part of such a shift would be the refusal by the Federal Government to renew all long-term leases by senior rights holders over the next three to five decades. With respect to fish protection, the current approach would have to be replaced with one in which a value is computed for any water allocated for fish protection. Furthermore, water markets would imply the termination of government subsidies for agriculture and changes in Federal administrative policy affecting the actual pricing of water if true value is to be reflected. Lessons can be learned from other situations, e.g., California, where such large-scale shifts have been made.

There must also be "... a central conveyance agency, regulated in the public interest at a high level of economic and financial sophistication, doing what a market would do if a market would work" [53]. State public utility commissions routinely perform this service in the areas of electric power, gas, and communications, among other things. Because the Bureau of Reclamation plays such an important role for irrigated agriculture, how the Bureau will function in the future is critical to increasing efficiency.

In addition to markets, the adoption of water banking combined with interstate transfers should also be carefully evaluated. A working example of a water bank exists in Idaho. The Water Supply Bank is a water exchange market operated by the Idaho Water Resource Board. Using the Bank, water users with rights to more water than they require in a given year can put the excess water in the Bank, from which it can be sold or leased to users who do not have enough to meet their needs. This system helps make excess water available to other users for irrigation or other authorized uses. Water Bank water also has proven valuable by providing stored water for downstream salmon recovery efforts. This Water Bank approach helps put the maximum amount of water to beneficial use, and is an example of how using market forces results in optimization of water use.

Water in the Bank involves two distinct categories of water: The first is natural flow water. This generally involves rights to surface water diverted from a river, stream, or groundwater. The Board directly controls the

sale or rental of water covered under natural flow water rights. The second is stored water, that is, water stored in "rental pools" in reservoirs. There are currently four rental pools operated by local committees in Idaho. They involve water from the Snake River upstream from Milner Dam near Burley (including a separate bank operated by the Sho-Ban Tribes), the Boise River and the Payette River.

In 1979 the Idaho Legislature formalized the program of annual leases of storage water entitlements. The legislation set into law a 1976 policy recommendation of the state water plan, which had called for the creation of a "water supply bank...for the purpose of acquiring water rights or water entitlements from willing sellers for reallocation by sale or lease to other new or existing uses." The responsibility for the water supply bank was placed under the Idaho Water Resource Board.

Beyond the price signal, demand management is likely to be responsive to a variety of other policy options which have been identified in a 1993 study by the Office of Technology Assessment [119] of the U.S. Congress. These focus on how the federal government could encourage conservation, without explicitly directing how the conservation would be achieved.

- Revise the tax code to facilitate conservation investment.
- Allow state revolving-loan funds to be used for conservation investments.
- Tie funding of state water projects to improved efficiency in management and consumption.
- Encourage adoption of risk management and risk minimization practices to mitigate drought effects.
- Encourage water conservation in federal and state facilities.
- Require demand management via modifying rate structure, reducing landscapes' use of water, modifying plumbing and irrigation systems to increase efficiency, educational programs, and metering.

Specific possibilities for reducing demand include:

- develop more efficient application methods of irrigated water, which could decrease water needed for agriculture
- reduce irrigated acreage
- adopt agricultural and land management practices that reduce soil moisture loss
- develop new technology that would allow for increased water use and efficiency
- use high-efficiency plumbing fixtures in new construction

2.5.2 Strategies for increasing the aggregate supply of water

Some of these options were suggested by the region's water managers who attended the OSTP/USGCRP workshop (see section 2.1 of Part I), and others upon further reflection by the CIG.

- encourage innovative methods of increasing water storage, including groundwater recharge schemes in which water is pumped into the ground during times of high runoff; new dams could also increase water storage, but there are few potential dam sites left on the Columbia and dams pose problems for salmon recovery
- seek new sources of water, e.g., groundwater
- develop strategies to encourage optimal use of existing water supplies of differing quality, for example, delivery of non-potable supplies (such as reclaimed water) for some uses
- manage water resources more effectively at the watershed level, making use of seasonal forecasts
- if water supply needs are in conflict with hydropower, could replace some hydropower capacity with conventional and gas turbine electrical plants
- increase cooperation, coordination, and information sharing among users to allow increased effectiveness of response to currently unknown climate effects

- improve system robustness and flexibility of water resources by connecting water supply systems with different characteristics (e.g., the proposed intertie between Tacoma and Seattle water supplies)

- build desalination plants (likely to be prohibitively expensive)

One additional option is to negotiate with Canada to increase storage in British Columbia with the PNW region as the prime customer for this water. Such binational issues would have to be evaluated much more carefully.

2.5.3 Strategies for increasing institutional flexibility

To most people, climate change is a vague, distant concept that has no relevance to their everyday lives. For PNW water resource managers, the same is generally true: climate change to date has not entered long-range planning activities. As a first step to understanding how water resource management in the Northwest could begin to plan for climate change, we outline here a study we conducted of the use of far more immediate climate information: seasonal forecasts. Seasonal forecasts, and the risks and benefits of incorporating them into short-range planning, are much more visible and immediate than the more distant concept of climate change projections. The study reveals some **profound institutional barriers to incorporation of climate change,** barriers heightened by (1) the recent turmoil as fish protection was legally given higher priority and (2) the impending further turmoil with the deregulation of the electric utility industry.

The study, conducted from 1996 to 1998, involved extensive interviews with approximately 40 water resource managers concerning their use of seasonal forecasts in planning and operational decisions (see Appendix B.2). Water resource managers monitor snow pack, precipitation, stream flows and other characteristics in order to estimate timing and quantity of flow based on their understanding of historic variation in these parameters, with a view to making seasonal streamflow forecasts. However, even though they could make forecasts, they generally lacked the capability to incorporate these forecasts into their management decisions [19, 20]. Thus, they were unable to take advantage of higher flows that are more likely to occur in the cool phase of ENSO; furthermore, nearly all were unaware of the Pacific Decadal Oscillation (see 1.1.2), whose influence on the water resources of the PNW is comparable to that of ENSO as shown in section 2.2. In fact, the chief operating rules for river systems were, still are, and are likely to remain, tied to the critical period of lowest flow years (currently 1936—37). This extremely cautious approach poses major barriers to exploiting the potential benefits of seasonal climate forecasts.

As the foregoing study illustrates, institutional redesign is the hardest category for addressing future shortages of water since it involves re-designing the institutional configuration as a whole, changing the roles of organizations within it, and possibly creating a new regional entity that would speak for the region as a whole on water issues and would plan adaptation strategies to meet the challenges of climate change. Such a task would be monumental in view of the administrative and regulatory environment of the region. The degree of fragmentation is extreme. Legislatures battle internally and with the governors; states squabble over upstream versus downstream rights to water; sectors press their proprietary interests; and administrative agencies confront restrictive case law and funding deficits. To take only one example, there is confusion and uncertainty even in the highest regional office of the Northwest Power Planning Council (NPPC) as to the science and conceptual foundations of salmon recovery. The current Fish and Wildlife Recovery Plan was criticized by the NPPC's Independent Science Group for being too focused on mitigation activities that have proven ineffectual to date and not focused enough on the habitat requirements and biological needs of the salmon. The Recovery Plan is an important issue because it represents so much of the environment under which managers and scientists now interact, especially with respect to the technical/sectoral approach to rehabilitation. And currently, meeting requirements for fish protection is the biggest challenge to the use of water for irrigated agriculture and hydropower production.

The other important factor for determining the management environment is the legal environment and on this account the situation has become more difficult. Recent case law in Washington state has in effect limited Department of Ecology jurisdiction and monitoring effectiveness. On top of this is the political and legislative intransigence on certain issues that directly obstructs both agency effectiveness as well as regional integration. The most recent vote in the Washington legislature rejected measures proposed by Gov. Gary Locke to establish a regional information exchange mechanism and to pursue "shared governance" in the form of a "regional integrated management body." Moving up the scale, the Northwest Power Planning Council is experiencing its usual difficulties with authorization and political in-fighting. It is an important regional body but one which is at least influenced by the political nature of

the appointees on the board. It does not hold any legal authority to implement salmon recovery policies at the state level, and it does not have a larger regional mandate to integrate information and decision making. Thus the legal environment in the Northwest today is not generally conducive to enhanced state administrative or regional authority.

At the same time, meaningful actions have been taken in a variety of places.

- Idaho water banking, for instance, is perhaps the most interesting because of the need to encourage water transfer and markets; if Idaho were to reinvest in the Bank we might wonder if water banks could develop in other states.

- The Corps' Systems Operation Review is intended to evaluate how well the Corps is meeting objectives and what changes need to be made. It has not so far produced very definitive nor politically feasible results, and thus may not result in any near-term dam removals, but it is still an important process and may indicate a tide change in how the federal government operates in the Northwest. It is yet to be seen whether the Corps and the Bureau of Reclamation will successfully transform themselves into management and planning entities.

- Fledgling conservation measures are being developed throughout the Northwest.

- Another important action that could make new criteria such as equity and wildlife conservation more salient is the upcoming process of dam relicensing by FERC; this may be an important trigger in the future, but it is probably unrealistic to expect that dams will be denied relicensing based on non-integrated and sectoral predilections.

- Finally, two significant pilot programs in Washington and Oregon have been created during the decade and may signal a powerful opportunity for greater participation of all stakeholders in the process of cooperative management. There are the Chelan Agreement in Washington, the Salmon and Trout Enhancement Program (STEP) in Oregon, and the new Oregon Salmon and Watershed Plan.

All of these efforts have adopted a watershed management focus. On their merit the programs may not be complete successes but they indicate that there is a necessary level of understanding about the need for local communities to become involved in solving problems of overallocation and habitat degradation in the Columbia and Snake Rivers before action will be taken and the need to take at least a water shed approach.

We therefore think that a focus on information capacity may provide an indirect way to solve the problem of institutional re-design in the Pacific Northwest. Federal and state agencies, city and coastal planners, and water resource managers are not adequately integrated in their sources of information or the comprehensiveness of their databases where climate variability and change are concerned. We know that there is variation in the quality of online water resource information for each of the state water resource agencies in the region and that the information that is online is not as user friendly as it could be. Federal, state, and academic resources could be combined to outfit at least a regional information-based water management service, founded in part on "rights imaging" and climate impacts analysis, and with a more sophisticated understanding of the links between natural ecosystems and human activities. Information capacity needs to be improved by expanding the links between federal and state agencies and by developing a regional resource database that is not beholden to single sectorally-determined special interests. A national climate service could serve this function nicely.

Let us illustrate this point about the potential power of information conveyed by a "neutral" climate service as a means of breaking through parochial framing of policy problems with information related to the response of Federal and State of Washington authorities to climate variability in the Yakima Basin. As mentioned in section 2.2.4, there were no Federal actions related to water management for more than 30 years after the establishment in 1945 of the distinction, and rights, between holders of senior water rights and holders of junior water rights; only since 1979 has the system been required to make adjustments, and there have been many. One could interpret this long hiatus as evidence that the federal action establishing the water rights system was essentially robust, but this interpretation would be dangerously wrong.

A correct interpretation would recognize that the problems stimulating Federal action in 1945 were

precipitated by the 1925—1945 positive phase of PDO which produced seven droughts, including what was possibly the most intense multiyear drought of at least the last 350 years in the Columbia River Basin [30]. Furthermore, the "robustness" of the Federal action in 1945 was completely an artifact of the negative phase PDO which lasted from 1946—1976, in which there were no significant droughts. In this period of plenty, the greatest growth in the Yakima Valley as an agricultural producer was allowed to occur. So when the next PDO reversal occurred in 1977, bringing another series of seven droughts, constant piecemeal remediative action was the order of the day. Now, there is some uncertainty as to whether the PDO changed phase in the mid 1990's, or even as early as 1989—1991. But, if it did, there would likely be more water all around as there was between 1946 and 1976. If the same kind of growth is allowed to occur, and if the PDO behaves as it has in the past, then some time in the next 20—30 years, the Yakima Valley is likely to be hit by another PDO reversal bringing multiple droughts, just at the time that the effects of climate change are likely to be more pronounced. **A major planning exercise would be a rational response to what we now know.** With this type of information in hand, policy makers would be much better equipped for water resources planning in the region.

In summary, the tangle of bureaucracies that have jurisdiction over the Columbia River system has so far proven remarkably unresponsive to climate variations or to long-term climate change. Constrained by institutional factors (built-in risk aversion), they are barely able to make use of seasonal forecasts, let alone long-range climate change scenarios. Fundamental redesign of the way water is managed may be required.

Outside the Columbia River basin, nimbler management systems like the water supply agencies in Seattle and Portland have proven more capable of using seasonal forecasts, sometimes with impressive results [52]. These offer a positive example of how to match demand with changing supply.

Case study: Seattle Public Utilities

In the case of Seattle Public Utilities (SPU), which supplies water to the City of Seattle and suburban purveyors, two recent summer droughts illustrate the capability of an institution to learn from and respond to adverse conditions [52]. In 1987, the summer began well with full reservoirs, but a hot dry summer was followed by late fall rains, and a number of problems developed. Hot, dry summers lead to both lower supply and higher demand, leading to the need for curtailments in water use and other impacts. In 1987, water quality declined, flows for fish were reduced, and water level got so low in the city's main reservoir that an emergency pumping station was installed. As a result of the 1987 drought, the Water Shortage Contingency Plan was developed. It laid out a plan of action for future droughts and facilitated institutional memory. The plan broadly describes four stages, each more drastic than the last: advisory, in which they merely inform the public of the possibility of a shortage and monitor various aspects of the water supply more closely; voluntary, in which they ask the public to reduce consumption; mandatory, in which certain types of water use (e.g., lawn-watering) are prohibited; and rationing, a stage that is still being developed.

In 1992, another drought occurred, for somewhat different reasons and with a rather different response. Abiding by flood-control rules, managers spilled water in late winter, but poor snowpack did not allow the reservoirs to reach their usual levels by the beginning of summer. In the spring, SPU sought voluntary reductions by all users. Following this, another hot, dry summer like 1987 meant that the mandatory stage was invoked. SPU restricted outdoor water use, including lawn watering and car washing. This restriction hit the landscape industry very hard: forced to let their lawns and landscaping perish, customers did not purchase new plants they could not water. The next winter, though, the landscape industry faced a boom as people replaced their withered yards and gardens.

Although the situation never reached the rationing stage, there were serious problems with water quality. The water failed the state's water quality standards on fecal coliform count; as a result, the city had to begin building a very expensive ozonation plant. Problems also developed with the water's taste and odor. High water temperatures probably had adverse impacts on salmon, though no measurements exist to confirm this.

Each year now, SPU predicts supply and demand using a model that includes historical climate and probabilistic predictions based on the phases of ENSO and PDO. For example, in an El Niño year, the chances of water shortage serious enough to warrant some actions is about 1 in 5, and appropriate actions can be taken. When an El Niño event occurred in 1997—98, such actions were triggered and a summer drought in 1998 went virtually unnoticed by the public, because adequate advance planning and improved system operations were sufficient to address the shortage. Snowpack was slightly below normal, and a hot dry summer led to greater demand. But SPU aggressively educated employees and a number of measures were implemented to conserve water or otherwise increase supply: for example, the reservoirs were allowed to fill higher than normal in order to protect salmon, and the use of water for normal in-house operations was reduced.

This success story of institutional learning is encouraging; however, even in nimble management systems like SPU, there is a long way to go in adapting to climate change on longer time scales. SPU plans for long term supply and demand, but has not formally begun to consider the impact that climate change could have. According to current projections, **demand will surpass supply within 15 years assuming no change in climate**. On that timescale, both the PDO and climate change clearly have the potential to affect summer demand and supply. If, as seems likely from the climate scenarios, summers eventually become significantly warmer, that factor alone would be sufficient to invoke the four-step Water Shortage Contingency Plan more often, with mandatory restrictions eventually being insufficient to avoid rationing.

Salmon

3.1 Current status and stresses

Salmon are anadromous (from the Greek *anadromos*, running upward) fish, swimming upriver to reproduce at the end of their lives. Few other organisms live, as they do, **part of their lives in freshwater and part of their lives in saltwater.** They spawn and rear as juveniles in fresh water, and typically mature and undergo most of their growth in marine environments (Figure 34). In cold streams, mature spawning salmon search out gravel beds where a male and female pair up to deposit and fertilize eggs in a redd, or nest. The fertilized eggs hatch into fry (small fish) several weeks later and these juveniles will remain in the stream from a few weeks to several years, depending on the species and geographic location. Juvenile salmon then undergo physiological changes to "smolts", a stage that prompts the still juvenile fish into their seaward migrations. For most species of PNW salmon, the smolt migration takes place in the spring and early summer months. This timing coincides with the typical onset of coastal ocean and estuarine upwelling seasons that fuel marine food-web productivity. In large, snowmelt dominated rivers in the region, the **smolt migration to the marine environment is also timed to take advantage of the high, fast stream flows** that come with the peak snowmelt period (the spring "freshet"). For smolts that travel hundreds of miles from the PNW interior, fast high stream flows are critical for speeding their migration to the ocean. Once in the ocean, smolts grow rapidly as they feed on typically abundant food resources. Maturing salmon spend anywhere from a few months to as many as 6 years at sea before returning to natal rivers to complete their life cycle. Most Pacific salmon die after spawning, and the marine-derived nutrients they carry back to their natal streams are now recognized as important nutrient sources for stream and riparian food webs.

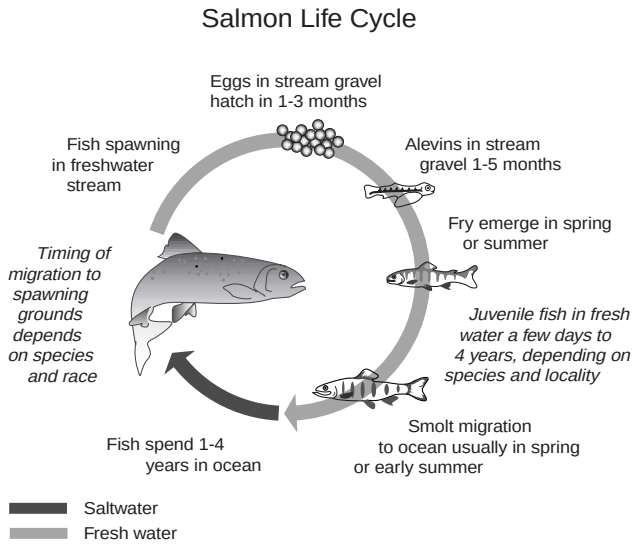

Figure 34. The life cycle of salmon. From [162].

In the northeast Pacific, there are five species of commercially harvested salmon. These are: pink (*Oncorhynchus gorbuscha*), sockeye (*O. nerka*), chum (*O. keta*), chinook (*O. tshawytscha*) and coho salmon (*O. kisutch*). Additionally, there are two species of non-commercially targeted salmon: steelhead (*O. mykiss*) and sea-run cutthroat (O. clarki clarki). Although there are only 7 species, scientists have long understood that sub-groups of the same salmon species typically form substantially isolated breeding populations that contribute to the ecological or genetic diversity of the biological species.

For the purposes of the Federal Endangered Species Act (ESA), these distinct population segments are treated as *stocks* or *evolutionarily significant units* (ESUs) of the species as a whole [77]. Once an ESU is identified, a variety of factors related to population abundance are considered in determining whether an ESA listing is warranted. In the PNW region there are dozens of ESUs for the 7 salmon species.

The ESA defines "endangered species" as "any species which is in danger of extinction throughout all or a significant portion of its range." "Threatened species" is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." According to the ESA, the determination of whether a species is threatened or endangered should be made on the basis of the best scientific information available regarding the species' status, after taking into consideration conservation measures proposed or in place [77].

In March 1999, the National Marine Fisheries Service listed 8 PNW salmon ESUs as threatened, and 1 as endangered [142] (Figure 35), bringing the current regional total to 24 ESUs. Especially notable in the latest listings is the inclusion of Puget Sound chinook, the first ESA listing in US history for a species inhabiting a highly urbanized area [144]. The ESA listing of Puget Sound chinook has sent shock waves through the region's political and economic circles, while listings of Columbia River and coastal Oregon stocks have had similar effects in those regions. The eventual socioeconomic fallout of the latest ESA listings will not be known for years.

Historically, salmon occupied virtually every accessible freshwater drainage in the PNW region, ranging from the smallest coastal streams to the largest drainage systems like the Columbia River and its tributaries. Today, PNW salmon have disappeared from about 40% of their historic range, and are in serious danger of extinction in most of their remaining habitat [112].

The severe problems facing PNW salmon are the result of a century of anthropogenic stresses, directly via over-harvest and indirectly via land use practices that have degraded and/or destroyed freshwater and estuarine habitats. For example, the upper Columbia River basin above Grand Coulee Dam and the Snake River basin above Hell's Canyon Dam are now completely inaccessible to salmon because of dams. Overall, about a third of the historic spawning and rearing habitat in the Columbia River basin has been lost to dam construction. Many dams have fish ladders, which are partially effective at allowing migrating salmon to pass. The once free-running Columbia River has become a chain of reservoirs. The altered hydrology has led to increased in-stream temperatures, reduced dissolved oxygen contents, increased dissolved nitrogen levels, and altered sediment loads and transports. In addition, intense fishing pressures have also played a major role in the decline of wild salmon populations in the PNW. The virtual elimination of beavers and beaver dams, decades of logging, construction of "splash dams" for transporting logs downstream, and widespread road building have negatively impacted both coastal and interior salmon streams [112].

Humans have also imposed growing stresses on salmon in the marine environment. These have included

- losses of estuaries and nearshore coastal habitats, particularly in more urbanized regions like the
- Puget Sound Basin, where estuarine habitat has been reduced by more than 50% in the last century
- the size and orientation of the Columbia River sediment plume has been radically altered during the 20th century [11]
- directed salmon fishing in the ocean
- harvest of other marine species, which alter their predation patterns on juvenile salmonids in the coastal ocean
- prolific hatchery releases of salmon smolts that in some cases may be exceeding historic (natural) smolt production and ecosystem carrying capacities.

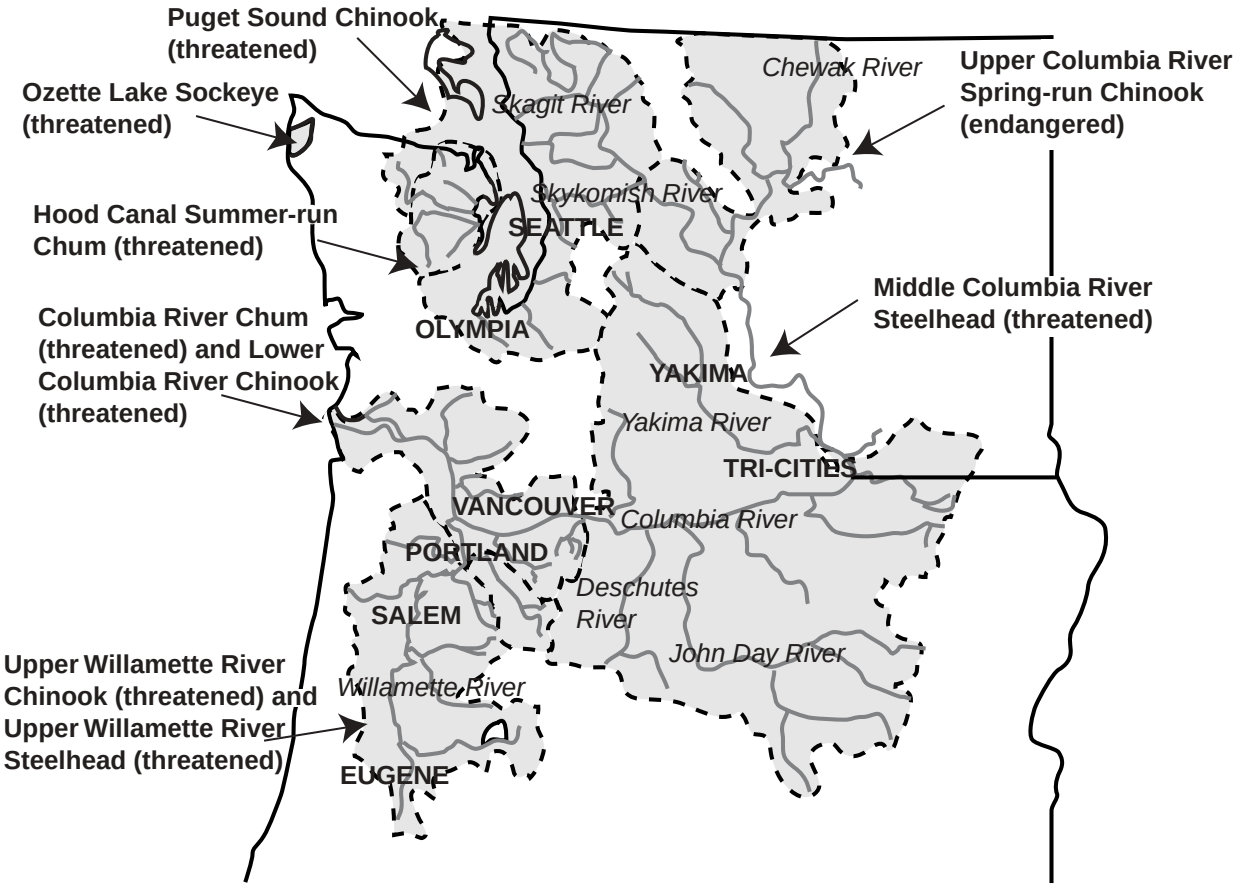

Figure 35. Areas affected by recent listings of PNW salmon under the Endangered Species Act.

Massive investments have been made in salmon hatcheries in attempts to rebuild and/or maintain sport, tribal, and commercial fisheries. In spite of this technological-fix approach, declines in both hatchery and wild PNW salmon stocks remain widespread, though not universal. The stresses outlined above affect Pacific salmon at every step of their unusual life cycle, and difficulties that they encounter in freshwater, estuarine, and ocean environments can impair their growth and survival.

A comprehensive review of the status of PNW salmon is listed in the National Research Council's 1996 report Upstream [112], page 75—76). The major conclusions of this report include the following:

- Pacific salmon have disappeared from about 40% of their historical breeding ranges in Washington, Oregon, Idaho, and California over the last century, and many remaining populations are severely depressed in areas where they were formerly abundant.

- Coastal populations tend to be somewhat better off than populations inhabiting interior drainages.

- Populations near the southern boundary of species' ranges tend to be at greater risk than northern populations.

- Species with extended freshwater rearing (e.g., coho salmon, spring chinook, and summer steelhead) are generally extinct, endangered, or threatened over a greater percentage of their ranges than species with abbreviated freshwater residence (e.g. chum or pink salmon).

- In many cases, populations whose numbers have not diminished are now composed largely or entirely of hatchery fish.

3.2 Past changes and the impacts of climate variability

Climate variability plays a large role in driving fluctuations in salmon habitat. These environmental changes in turn alter the ecological communities of which salmon are a part. The key aspects of this climate-induced variability are: changes in the availability of food, competitors for that food, and the predators that prey on small salmon. Measurements of phytoplankton at the bottom of the marine food chain are too scarce and sporadic to draw quantitative connections with year-to-year variations in climate, but we can look directly at the year-to-year variations in salmon abundance and smolt-to-adult survival rates to infer the intermediate connections between climate and salmon abundance.

Salmon are sensitive to a variety of different climate variables at different times in their complex life cycle (Figure 34). Incubating eggs in gravel nests are vulnerable to stream-scouring floods. Developing juveniles (fry and parr) require relatively cool, oxygen rich flows to survive the warm low-flow summer and fall seasons typical of PNW streams. Migrating smolts are faced with new types of food and predators, as well as dramatically increased salinity, as they travel from streams through estuaries and eventually into the coastal ocean. Adults must survive in the open ocean, where they have greater flexibility in foraging (some travel thousands of miles) and can descend to some depth to find better conditions, but where they also face numerous predators and in some extreme years, a lack of available food. Finally, adults returning to streams on their spawning migration are sometimes faced with thermal barriers when stream and estuary temperatures reach approximately 70—74˚F (21—22˚C) [103].

Recent studies suggest that **is at the migrating smolt stage that salmon are the most vulnerable to climate variations** [124]. For example, the timing of their arrival in the coastal waters can play a big role in their survival. If smolts arrive before the onset of summer northerly winds that upwell nutrient-rich sub-surface water, the migrating smolts will be faced with a relatively scarce food supply and become fairly easy prey for other predators like diving birds. If the smolts arrive too late, the spring bloom of phytoplankton may have begun to decline and other species, including other runs of salmon, may have depleted the food supply.

Climatic factors also influence the type, distribution and abundance of predators, which in turn influences survival of juvenile salmon [124]. Along the Pacific Northwest coast, the seasonal migrations of oceanic predators such as Pacific hake and Pacific mackerel are keyed to sea surface temperatures. In especially warm coastal ocean years (often related to both ENSO and PDO processes; see Figure 6), large schools of predatory fish arrive in the PNW coastal ocean earlier in the year and are closer to shore, increasing predation pressure on salmon smolts during their first few months in the ocean. During exceptionally warm years (like those coinciding with the 1982—83, 1991—92, and 1997—98 El Niño events), Pacific mackerel have been known to virtually eliminate entire hatchery chinook smolt plants as they enter estuarine waters off the west coast of Vancouver Island [67].

Despite the broad similarities in the lifecycle of various salmon species outlined in the previous section, there are also wide variations in behavior of individual stocks. Some spawn and hatch thousands of kilometers from the ocean; others only a few kilometers from the ocean. Some migrate seaward after a few weeks, some after a few years. The range of behavior leaves different stocks sensitive to environmental conditions in different ways, and consequently it most be borne in mind throughout our discussion of the impacts of climate variability and change that behind any broad generalizations about how climate affects salmon lies a rich diversity of behaviors; what applies to one salmon run, or even one salmon species, may not apply to all.

Nonetheless, **most salmon stocks throughout the north Pacific show clear sensitivity to environmental changes associated with the Pacific Decadal Oscillation** (PDO; see page 13 for definition). Investigators in the UW Climate Impacts Group ([61, 101]) have been instrumental in establishing the connection between the PDO and salmon abundance in the PNW and Alaska. Alternating phases of the PDO have corresponded remarkably well to alternations in the relative abundance of salmon in Alaska and in the PNW (Figure 36). (Variations in salmon catch between the late 1930's and early 1990's are almost entirely due to abundance, not to fishing effort [7].) In the PNW, salmon tended to be more abundant during the cool phase of the PDO (1946—76) than in the warm phases (1925—45 and since 1977), while the reverse was true for Alaska. It is thought that the lower abundance in the PNW during the warm phases of the PDO occurred because the coastal near-surface ocean was warmer, more stratified, and hence less nutrient-rich, and that predation by Pacific mackerel was exceptionally high.

The relatively high salmon production in Alaska during warm PDO eras is thought to arise in part because a warmer, more stratified ocean in the coastal waters of Alaska benefits phytoplankton and zooplankton production. The cool waters in The Gulf of Alaska are almost always nutrient-rich, but strong stratification is needed to keep phytoplankton near the surface where energy from the high-latitude sunshine is limited. In the PNW's coastal ocean, lack of nutrients from increased stratification is most often the limiting factor in phytoplankton production [54].

Since 1977, the PDO has been primarily in the warm phase, and salmon production has generally been very high in Alaska and poor in the PNW. As previously noted, in recent years enormous investments have been made to maintain and enhance numbers of threatened and endangered salmon stocks in the PNW region. It has been suggested that a lack of immediate increases in production following restoration efforts may be misconstrued as management failures in periods of poor ocean conditions like those that have prevailed since 1977 [61].

Recent studies (e.g., [61]) indicate that the north-south inverse pattern of salmon production is better correlated with the long-lived climate changes associated with PDO than with the year-to-year climate variations associated with El Niño-Southern Oscillation (ENSO; see page 13 for definition). At first glance, this result might seem surprising since warm phases of ENSO and PDO have similar impacts on the ocean and terrestrial environments in the PNW. There are, however, a number of reasons for the greater sensitivity of salmon to PDO. First, salmon appear to be most sensitive to climate variations as smolts, but are not counted or measured until they are caught 1—4 years later (depending on species). Consequently, when making connections between a history of ENSO events and a history of salmon catch, one must consider the typical age of a given species when caught and look at the ENSO state in the year those fish probably entered the ocean; but not all fish of a given species spend the same number of years in the ocean, so the year-classes are smeared together somewhat. Second, during its lifespan an individual fish may feel some beneficial effects of ENSO in one year and some deleterious effects of the opposite phase of ENSO in the next year. The abundance and average weight of salmon thus depend on several years' conditions. Unlike ENSO, the PDO has significant year-to-year persistence, which may help to explain why salmon in the PNW do not exhibit as strong a dependence on ENSO as on PDO.

Puget Sound, the finger of salt water that protrudes deep into Washington State from the Pacific Ocean, is a transition zone between the freshwater and open ocean environments. It also feels the influence of climate variations (like those associated with ENSO and PDO) from both the freshwater and ocean environments: climate variations over land influence the volume, timing, temperature, and turbidity of runoff, while climate variations in the ocean influence oceanic temperature and stability, which in turn affect the properties of salt water entering the Sound through the Strait of Juan de Fuca. In the cool phase of ENSO or PDO, precipitation is often above normal and temperatures are below normal, leading to a greater volume of runoff in the winter and, for those rivers with a significant portion of their catchment in the mountains, a greater volume of runoff from spring snowmelt. Consequently, freshwater input at the surface of Puget Sound tends to be greater than normal. The cool phase of ENSO and the cool phase of PDO are also associated with lower surface temperatures and lower stability in the coastal ocean. Opposite relationships are associated with the warm phase of ENSO and the warm phase of PDO.

In contrast to the open ocean, Puget Sound appears to buffer salmon against changes in ocean properties associated with ENSO and PDO [131].

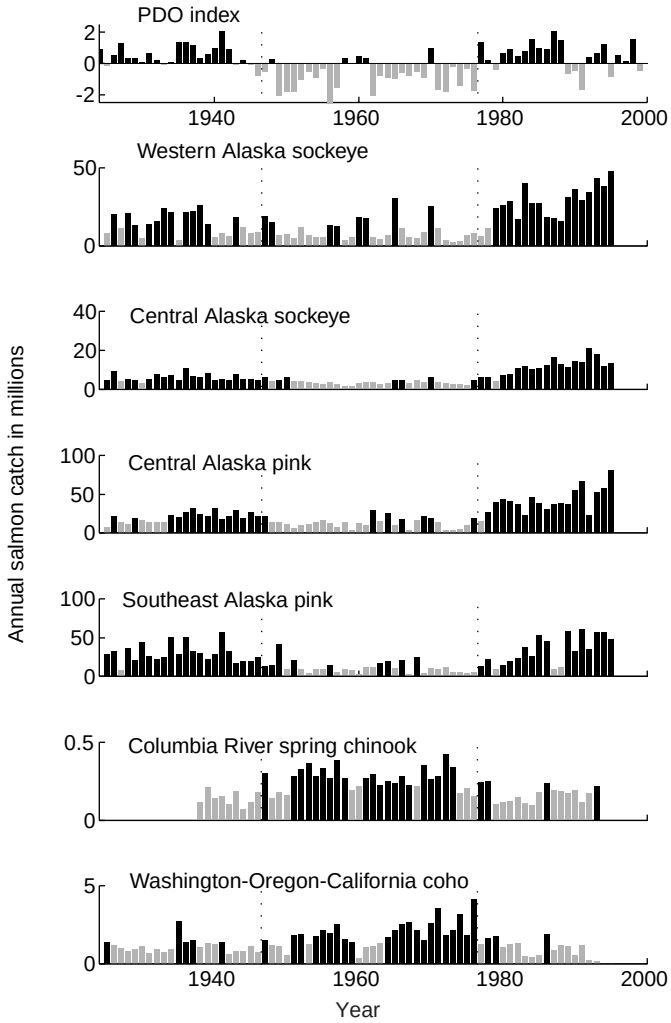

Figure 36. Selected Pacific salmon catch records with PDO signatures. For Alaska catches, black (grey) bars denote values that are greater than the long-term median. Light dotted vertical lines are drawn to mark the PDO reversal times in 1925, 1947, and 1977. The PDO index from Figure 6 is shown in the top panel. Reprinted from [101].

Correlations between ENSO or PDO and Puget Sound salmon abundance are much weaker than for Pacific salmon stocks. The estuarine environment, by ensuring a more gradual transition in salinity for the vulnerable smolts, may provide Puget Sound salmon with greater resilience to climate variations.

3.3 Possible future changes and the impacts of climate change

Salmon are clearly sensitive to a variety of environmental factors that are influenced by climate. Much work remains to

be done, however, to determine how important these climate-related factors are to salmon health and survival, especially in the oceanic portion of their life cycle. Looking to the future, the possible changes in these factors are very uncertain. Climate models lack the spatial resolution and detailed representation of critical physical processes that would be necessary to simulate important factors like coastal upwelling and current variations. An important question in considering climate change in the north Pacific is how patterns and frequencies of climate variations (like those connected with ENSO and PDO) will change in a warmer world. As outlined in section 1.2.5, different climate models give fairly different answers on this question and it is still quite uncertain how the existing variability of the Pacific ocean will change.

For the factors that climate models can simulate with some confidence, however, the prospects for many PNW salmon stocks look bleak. The general picture of increased winter flooding and decreased summer and fall streamflows, along with elevated stream and estuary temperatures, would be especially problematic for in-stream and estuarine salmon habitat in the PNW. For salmon runs that are already under stress from degraded freshwater and estuarine habitat, these changes may cause more severe problems than for more robust salmon runs that utilize healthy streams and estuaries (some of which still exist in the PNW, and many of which still exist in Alaska).

3.3.1 Freshwater environment

Several studies have given results about how anthropogenic climate change might affect the freshwater environment of different species of salmon. Heat-related mortality is an important limitation, but other limitations may be as important or more important. Some studies [8, 135] indicate that the most important factors for£**juvenile coho** freshwater survival are (1) the in-stream temperature during the first summer, combined with the availability of deep pools to mitigate high temperatures; and (2) temperature during the second winter, combined with the availability of beaver ponds and backwater pools to serve as refuges from cold and high stream flow events. Consequently, increases in summer water temperature will affect coho most if they occur in combination with decreases in summer stream flow, a change implied by all the future climate scenarios applied to hydrology models for the Columbia River, its tributaries, and other snowmelt-dominated rivers (Figure 27).

Chinook salmon fall broadly into two categories: ocean-type and stream-type [65]. Ocean-type chinook migrate to sea only a few months after hatching, then spend several months in a coastal estuary, and live most of their lives in coastal ocean waters. Stream-type chinook spend more time in the stream after hatching (typically 1 to 2 years), travel widely in the ocean, and return to their natal stream several months before spawning. These two different types of chinook have rather different sensitivities to climate. Overall, freshwater survival seems to be higher for stream-type chinook than ocean-type chinook because they tend to occupy parts of watersheds that are more consistently productive and less susceptible to dramatic changes in water flow. Ocean-type chinook tend to use estuaries and coastal areas more extensively for juvenile rearing perhaps in response to the limited carrying capacities of smaller streams, less productive watersheds and highly variable seasonal flooding in the lower portions of many watersheds. Along the Oregon coast and north, summer estuarine temperatures appear to be cold enough to allow young fall chinook an important sheltered habitat. The period of estuarine residence for ocean-type chinook also varies regionally, being the greatest in the open ocean estuaries of Washington and Oregon and least in the sheltered coastal estuaries of Puget Sound and British Columbia.

Stream and estuary temperatures of 21—22˚C and above are known to cause severe problems for PNW salmon of all species. “It has been well documented that temperatures of approximately 21—22˚C establish migration barriers to most adult salmonids. Delays in migration that have been observed are significant enough so that the probability of surviving to spawn or to reach spawning grounds in time to spawn becomes low” [103]. At present, thermal extremes such as these are thought to be relatively uncommon in the PNW region. However, there were numerous anecdotal reports of thermal barriers to spawning salmon migrations in the summer of 1998 for Lake Washington chinook and Fraser River sockeye (Randy Schumann, King County Metro, pers. comm., 1999). A key question that needs to be addressed is how the frequency and duration of periods with stream and estuary temperatures in excess of 21˚C will change with anthropogenic climate change.

3.3.2 Marine environment

One important effect of climate change suggested by the climate models stems from the decrease in spring snow pack. Our hydrology modeling work suggests that the spring freshet, in which melting snow increases river flow, will probably occur earlier in the calendar year (Figure 27). Some species of salmon rely on the freshet for a quick journey to the ocean and, as noted above, their survival and growth depends on the timing of their arrival in the ocean compared to the timing of the onset of northerly winds, which bring upwelling and increase the food supply at the base of the marine food chain. Climate models are not yet suitable for determining whether the timing of the onset of northerly winds will change in the same way as the timing of the freshet. However, in the 1980's and 1990's the onset of northerly winds has tended to occur *later* in the year than that observed in the 1960's and 1970's [15].

One recent study [161] suggests that a warming of the North Pacific Ocean associated with doubling CO_2 would be sufficient to push the range of some Pacific salmon further north and out of the Pacific entirely. This study posits the following: (1) Pacific salmon are surface oriented; (2) sockeye salmon (in particular) are metabolically constrained by surface ocean temperatures; and (3) surface temperature increases simulated by current generation climate models will be sufficient to warm the North Pacific Ocean to a point that sockeye salmon will be forced into the Bering Sea (or beyond) or otherwise face starvation as their feeding cannot keep pace with their accelerated metabolic rates.

On the other hand, this notion of "thermal limits" to the ocean distribution of Pacific salmon has been challenged by recently obtained and analyzed data storage tags, which track the water temperature encountered by the tagged fish [159]. The tag data provide direct evidence that Pacific pink, coho, chum and steelhead salmon utilize a wide range of thermal habitats (presumably via vertical migrations between the surface ocean and sub-thermocline waters) on hourly and daily time scales. These tag data, along with high-seas sampling studies of salmon and their feeding habits, suggest that the link between the ocean distribution of salmon and ambient ocean temperatures is likely through environmental influences on marine food-webs [159, 125].

In the spring of 1999 archival tags were placed on adult sockeye salmon that were netted while swimming in the open waters of the North Pacific. One tagged sockeye was recovered in early August, 1999, in Taku Inlet (southeast Alaska). The temperature data recorded by this tagshows that this sockeye salmon, like the salmon sampled in the previous year, used a wide range of thermal habitats at hourly and daily time scales. Combining the temperature data with measured water column properties suggests that this fish exhibited significant vertical migrations, mostly in the top 30 meters (100 feet), with infrequent dives to 40—85 meters (130—280 feet) (K. Myers, pers. comm.). These data, while from only a single sockeye, cast further doubt on the notion that sockeye salmon are especially sensitive to surface temperature variations.

3.4 Socioeconomic impacts of the likely changes

In the past decade, sharp restrictions on fishing opportunities (for commercial, tribal, and sports fishers) have already had devastating impacts on the local economies that formerly revolved around salmon fishing. The recently signed Pacific Salmon Treaty with Canada has further reduced US commercial harvest opportunities for fishers that targeted sockeye salmon bound for Canada's Fraser River. Generally speaking, the once thriving PNW salmon economy has all but collapsed in the past few decades as a consequence of the decline in PNW salmon numbers and concomitant efforts to protect and restore remaining populations.

Recent changes in the operation of the Columbia River hydrosystem have also had large economic impacts. The price tag for Columbia River salmon enhancement and recovery activities is approaching $400 million per year (largely due to lost hydropower revenues, the downstream barging of Snake River salmon smolts, hatchery operations, and other salmon enhancement and recovery activities) [13]. Much of the lost hydropower revenue stems from the recent implementation of a policy recommendation known as the "Biological Opinion", or BiOp, which has elevated the priority of fisheries considerations in determining operational stream flows.

In the near future, there are widespread fears that declining numbers of wild PNW salmon will force socioeconomic hardships on a much broader scale, one that dwarfs that of the fishing industry and that of other Columbia River interests. These fears are just beginning

to be realized. As previously noted, the recent ESA salmon listings included the Puget Sound chinook ESU, the first ESA listing in the nation to affect a major urban area. Likewise, additional changes in regulations governing land and water use are expected throughout the PNW region where salmon ESUs have been listed under the ESA. Even in the summer of 1999, a period with exceptionally abundant surface water supplies (due to a record snow pack), the National Marine Fisheries Service has suspended some permits for water withdrawals from tributary streams in the Columbia River Basin because of ESA compliance considerations [143]. Battle lines between private property owners and government agencies are just starting to emerge from the fog of the recent ESA listings.

The socioeconomic fallout of the Puget Sound listing is expected to be especially large, and has galvanized political action at the regional, state, county and local government levels. For example,
Washington State's Governor Gary Locke has created a *Salmon Recovery Team* that has drafted a planning documented titled "Extinction is not an Option" [98]. This report contains comprehensive plans for new land and water use policies aimed at halting and reversing practices that harm salmon habitat. Political leaders throughout the PNW region are crafting similar plans with hopes of heading off federal mandates to comply with the ESA.

One of the greatest challenges now facing regional policy-makers are the bureaucratic hurdles involved with the multi-jurisdictional nature of the salmon problem [98]. Coordination between city, county, state, tribal, and federal (both US and Canadian) agencies lies at the heart of recovery strategies. These efforts are rapidly evolving, and there is little consensus about what PNW salmon recovery efforts will do to the generally healthy and expanding PNW economy.

Climate variations have clearly played a role in PNW salmon history, and are expected to be important in the future. Some have suggested that unfavorable ocean conditions associated with the warm phase of the PDO may have masked management efforts aimed at rebuilding PNW salmon numbers in the past two decades [61]. If the regional climate change scenarios that call for rising snowlines, increased flood frequencies, an earlier spring melt, and a generally warmer North Pacific Ocean are realized, it seems highly likely that anthropogenic climate change will add to the already long list of human-caused stresses that now plague PNW salmon (see section 3.1). By extension, increased stress on the already suffering PNW salmon populations would be expected to add to the already growing list of public policy measures aimed at protecting threatened and endangered PNW salmon.

3.5 Coping options for resource managers

In the open ocean, the effects of commercial and recreational salmon fishing in the PNW once rivaled those of climate variability, but most marine salmon fisheries are now either closed or severely restricted. In the freshwater phase of the salmon life cycle, however, the anthropogenic effects of clear-cutting, road building, and habitat degradation clearly outweigh the effects of 20th century climate variability.

While we know that PDO shifts tend to have large, pervasive impacts on whole marine communities, we are unable to predict what ecosystem shifts will occur in the future and how these will impact predator-prey relations. Consequently, managers claim there is relatively little they can do in response to advance knowledge of climate. Over the years, fishery managers have developed techniques for estimating stock abundance for the purpose of setting total allowable catch. These techniques involve detailed monitoring and in-season allowable catch adjustments which make it less important for managers to know

The *benefit of an increased understanding of the relationship between salmonid success and climate variability appears to be that it would allow managers to be more precautionary*, i.e., a particular phase of the PDO or a highly confident ENSO-related climate forecast might indicate the need for more conservative management measures than would normally be taken. Measures could include conservative harvest limits; additionally, conservative releases of hatchery smolts would be warranted if a priority was given to enhancing the survival of naturally produced salmon smolts.

However, fishery management rules are changing. Under the Sustainable Fisheries Act (SFA) of 1996, the over-fishing level determination with respect to salmonids and other species may change harvest targets markedly. Developing ecosystem approaches under the SFA may also alter management approaches. Both changes would tend to lower harvest rates on a stock-specific and ecosystem

basis. This could reduce stress and build a greater resilience, since ecosystems that are already stressed are likely to be most vulnerable to climate variability and change. For some species, a move toward decreased commercial harvest and greater recreational harvests could change the nature of management decisions. In Washington State, management decisions tend to be distributive in nature, i.e., who gets how much; and these can only be exacerbated by climate variability. It remains to be seen whether seasonal climate forecasts could actually assist managers in making allocation decisions for marine fisheries [132].

In the longer term, efforts to prevent further declines in salmon stocks in the PNW should take account of the potential consequences of climate change. Some efforts may be fruitless in the face of changing climate, whereas others may show more promise. Much more scientific and policy analysis is needed to determine how climate change information should be incorporated in salmon recovery plans.

Strategies to improve the viability of salmon in the face of climate change would necessarily focus on the freshwater portion of their life cycle, where our scientific understanding is greatest and where human influence is greatest too. Revisions in reservoir operating procedures brought about by BiOp (see previous section) may provide some buffering to salmon by increasing stream flows during the late summer and fall, but as the PNW warms and peak stream flow shifts earlier in the year, this will become more difficult. It may be possible as well to change operating procedures or build new structures that would, for a time, slow the increase in water temperature in the rivers. But because salmon have a threshold temperature of 70—74˚F (21—22˚C) above which they rapidly lose health and die, an inexorable increase in water temperature would eventually overwhelm adaptation efforts in the most vulnerable stream and estuarine environments.

It is clear that variable ocean conditions have a significant impact on the overall production of all species of Pacific salmon, and that climate and ocean variability act at a number of time and space scales (e.g. seasonal, annual decadal time scales and global, regional and local space scales) to affect salmon production dynamics. Unfortunately, the scales we understand least about (seasonal and annual time scales; local space scales) are the ones that appear to be most important to salmon management, at least as it is presently practiced. Thus, it is very difficult, if not impossible, to "engineer" salmon management to match anticipated ocean conditions. Perhaps the most sensible approach is that advocated by Bottom [14], who urges that we adopt an ecosystem view towards salmon management. Thus rather than try to circumvent essentially unpredictable climate variations (both natural and anthropogenic) through the use of technology, or ignore it through the use of deterministic predictive models, we should "embrace environmental variation as an essential organizing property of living systems." Perhaps the purpose of conservation, including conservation in the context of fishery management, should not be to "improve" nature by eliminating variability; it may prove more effective to protect the interrelationships that allow populations and communities to sustain themselves in a changing world.

We only need to look as far as salmon populations themselves to see how this is done. For millennia, salmon have had to deal with the kinds of changes recently thrown at them by the climate system (e.g., decadal time scale changes in the mid-1970's, and large environmental changes associated with the 1997—98 El Niño and 1998—99 La Niña). Salmon have thrived in highly variable and unpredictable environments by evolving a diversity of life history strategies such as mixed year classes, extended smolt migration periods, lengthy adult spawning migrations and other strategies to hedge their bets against the uncertain freshwater, estuarine and ocean environments they are *always* confronted with. And thus within metapopulations (e.g. Columbia River coho salmon), a diversity of genetically hard-wired behaviors provides the key buffers to the climate-driven uncertainties that must be confronted from season to season, from year to year, and from decade to decade.

In this context, management should focus on maintaining the diverse metapopulation "parts" of the whole. In this view, resilience is directly related to diversity, and diversity is directly related to the availability of healthy and complex freshwater and estuarine habitat. To say that an ecosystem is "healthy" is to say that the overall system maintains sufficient complexity and flexibility to protect its self-organizing qualities [118, 41]. It must have the capacity to respond to change. In this context, "management must have as its central goal the protection of the system's creativity" [118].

Again quoting Bottom [14], "the emphasis on ecosystems reflects a growing awareness that we cannot maintain even our most carefully managed resources apart from the biophysical context that created them." The main point, then, is that in order to preserve the capacity of

Pacific salmon to respond to variable and unpredictable ocean conditions, we must preserve and restore intact and connected freshwater and estuarine habitat. Once this point is firmly institutionalized, the salmon will do the rest.

There are four things that can be done by managers to ensure that this ecosystem world view of salmon management is incorporated.

1. Do everything possible to preserve wild salmon population diversity through the conservation and restoration of freshwater and estuarine habitat. Degrading or eliminating pieces of the habitat leads to a simplification and destabilization of the salmon metapopulation structure of a region.

2. Avoid fishing practices that are selective towards specific metapopulation components. Francis [41] points out that in the case of Bristol Bay sockeye, nature has dealt the system at least as much variability, in both the short (annual) and long (decadal) term, as the (apparently) sustainable fishery has been able to remove at its peak. Thus with its freshwater and estuarine habitat in virtually pristine condition, the Bristol Bay sockeye ecosystem has evolved and maintained the capacity of absorbing significant levels of ocean-induced variability over multiple time scales, even in the presence of the largest single-species salmon fishery on the planet. One should note that Alaska fishery managers make every effort to spread the fishery out over as broad an array of system components as possible.

3. Manage hatchery programs to avoid negative impacts on wild stocks. In particular this requires the management and control of the release of hatchery fish as well as their harvest. In general, fishery managers need to develop ecologically based performance standards and monitoring programs to insure that the risks of hatchery programs are minimal [14].

4. Conservation and management must be based on sound science.

This last point seems obvious but is often ignored in the rush to satisfy short-term political agendas. As Bottom [14] points out, “prudent ecosystem conservation is not the same as quantitative prediction. It is a deliberative process of informing both citizens and decision-makers so that they can choose wisely despite the many ecological and cultural uncertainties involved in any management choice.” Holling [68] argues that there are at least two”“streams” of science. In the first stream, the machine metaphor for nature pervades. Management is oriented to smoothly changing and reversible conditions, and operates under the view that one needs to know before taking action. In the second stream, which Holling [69] argues is more appropriate for approaching ecosystem issues, the view is that knowledge will always be incomplete. And so in order to be a science for management, uncertainty and surprise must become an integral part of a sequence of actions, one dependent on the results of how the system responded to those that have come before [41]. This, then, is a science that openly acknowledges indeterminacy, unpredictability, and the historical nature of resource issues. The scientific problems faced by taking an ecosystem view are not amenable to solutions based on knowledge of small parts of the whole, nor on assumptions of constancy or stability of fundamental relationships”— ecological, economic or social. In this context the focus best suited for management policy is “actively adaptive designs that yield understanding as much as they do product” [68].

Forests

4.1 Current status and stresses

Evergreen coniferous forests are a dominant vegetative formation in the PNW and provide a broad array of goods and services for human society. These forests are typically abundant, lush, and massive; indeed, northwestern forests (west of the Cascade crest) are among the most productive in the world and can accumulate world-record amounts of organic matter. Because of their richness and the mild, wet climate, people often assume—incorrectly—that these forests are largely insensitive to climatic fluctuations.

The distribution of tree species and the length of growing season are strongly influenced by the warm, dry summers of the PNW (Figure 3) [43]. The **warm, dry summers have both direct and indirect negative impacts** on forest establishment, growth and persistence. The direct impacts include limiting the establishment of tree seedlings (on sites where the forest has been removed) and limiting photosynthesis in established trees for several months every summer. As an indirect impact, the dry summers also create conditions favorable for ignition and spread of wildfires, which is the most common natural cause of forest destruction [1].

The sensitivity of the temperate coniferous forest region of the PNW contrasts with circumstances in most other moist to wet temperate regions throughout the world, such as eastern North America, eastern Asia (including Japan), and Europe. The native vegetative cover of these regions is typically dominated by deciduous and, in warmer regions, evergreen hardwoods (angiosperms). Unlike the PNW, these regions have climates in which rainfall is well distributed throughout the year; i.e., extended periods of moisture deficit are not typical.

Forests in the PNW have been dramatically and permanently altered by settlers during the period of settlement beginning in about 1850. The primary direct impacts of humans have been to convert much of the forest cover at low elevations to other uses, such as agriculture and communities, and to alter the remaining forests by converting the massive old-growth forests to young managed forests. Shifts in the forest cover in the region have resulted in significant fluxes of sequestered carbon to the atmosphere [63] with current estimates at about 2 billion metric tons of carbon released during this century.

The natural occurrence of forest fires has also been reduced through fire suppression programs beginning early in this century although a recent change in philosophy has recognized the importance of fire to natural systems. There are major differences in the fire regimes west and east of the crest of the Cascade Mountains. Forests west of the crest are subjected to catastrophic fire events at intervals of several centuries [1]. Forests east of the crest, with a drier climate and more open-canopied structure, have historically been subjected to relatively frequent, lower intensity fires; here fire suppression has allowed for large increases in forest fuels and created the potential for higher intensity fires [134]. The suppression of fires has, however, led to greater sequestration of carbon in the unburned forests.

Clearcut logging has greatly fragmented forest landscapes and increased the area of "edge" relative to "interior" forest conditions [44]. One consequence is a reduction in habitat for species that dwell in the interior of forest stands, stands being defined as a spatial unit which is uniform in composition or structure and contrasts with surrounding areas. Another consequence of clearcutting has been an increase in the susceptibility of forests to windthrow.

Removal of forest cover, loss of older forests, and construction of logging roads have reduced the ability of forests to regulate the hydrologic regime, particularly in terms of maintaining late-summer streamflows, moderating peak

flows associated with rain-on-snow storm events, and reducing the potential for erosion. Peak (flood) flows are often dramatically increased on and downstream of areas with extensive clearcutting and road construction [79]. In-stream water quality, the physical integrity of stream channels, and other aquatic habitat characteristics are also impacted by clearcutting. In some cases these changes have reduced the ability of stream systems to support native fish species and other aquatic organisms.

4.2 Past changes and the impacts of climate variability

Climate variability, on a range of timescales, has impacts to varying degrees on individual trees, overall forest structure and composition, and disturbances. Individual trees clearly are sensitive to year-to-year variations in climate; in fact, the width of tree growth rings is one of the best records available of past climate.

Several studies have shown the direct effects of climatic variations on trees and forests in the PNW, mostly for areas close to the climatic limits of forests at upper (cold) and lower (dry and/or hot) timberlines. At upper timberline, tree ring analyses of mountain hemlock (*Tsuga mertensiana*) demonstrate tree growth responses to climatic variations. Decade-to-decade variations show a good correlation with the PDO (Figure 37). Also at upper timberline, significant tree invasion of subalpine meadows is associated with light snowpacks and long growing seasons [45, 136, 148, 163]. Near the lower timberline, tree ring analyses of ponderosa pine (*Pinus ponderosa*) show reduced growth associated with extended periods of drought (Figure 37). However, at middle elevations in the interior Northwest, and in the western hemlock and Pacific silver fir zones west of the Cascade crest, the structure and composition of most mature forest stands have little measurable sensitivity to climate variations. This insensitivity occurs because, on most forest sites, other factors such as competition obscure climatic signals in individual trees. Forest stands—once established—have the ability to buffer themselves against variations in climatic conditions [17, 25].

In addition to the above direct effects, climatic variations influence forest conditions indirectly through changes in the frequency or character of disturbances, especially wildfire. High-intensity disturbances are very important because they result in high mortality in

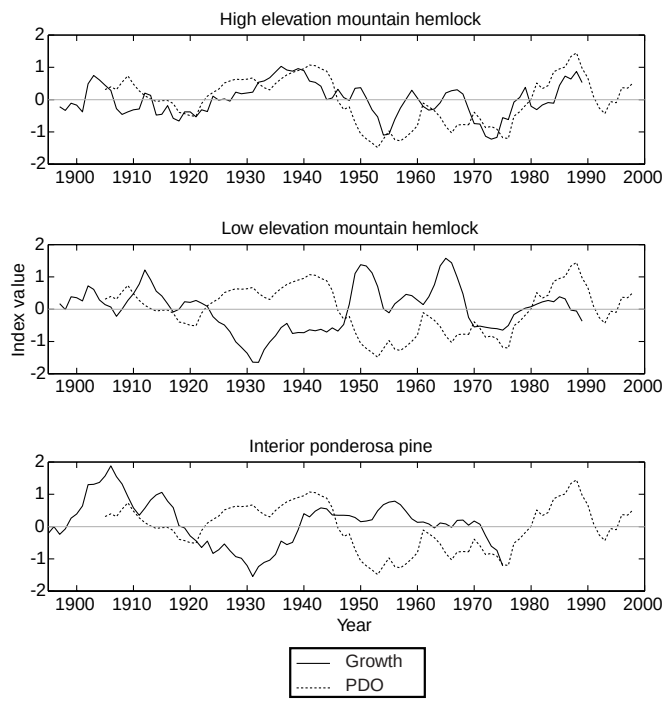

Figure 37. Smoothed annual growth rates for different types of trees at different elevations, compared with the PDO. From [129].

established forests, which have high levels of resistance to climatic variations. High-intensity disturbances reset forests to the establishment stage, which is the stage most sensitive to adverse environmental conditions, such as drought and heat [17]. Changes in the frequency and intensity of disturbances will affect ecological succession, particularly if summers become both warmer and drier. For example, increased disturbance in Pacific silver fir forest combined with warmer, drier summers that may limit the re-establishment of silver fir, may result in transition to Douglas fir-dominated forests at middle elevations.

Consequently, in looking for quantitative connections between forests and climate variability, we have turned to studies of disturbances both because of the importance of such disturbances and because climate change will probably alter the frequency and intensity of such disturbances [120, 140, 39]. Furthermore, catastrophic disturbances to forests, rather than changes in growth rates of individual trees, are likely to be the mechanism by which climate change will be most dramatically experienced, since established forests have substantial ability to buffer themselves from climate variations and change. Established forests often can resist climatic variability both because they ameliorate microclimatic conditions beneath forested canopies and because mature trees can survive extended periods of unfavorable climate [17, 25, 46]. Disturbance dynamics are of fundamental importance in determining forest ecosystem structure, function, and composition. For instance, changes in forest structure and composition have occurred in much of the interior Northwest during this century because of the effects of fire suppression [133]. Model simulations of forest succession under altered disturbance regimes suggest that ecosystem transitions will continue to occur over the foreseeable future in the interior Northwest. Understanding the connections between disturbance dynamics and climate variability is thus central to predicting the response of forest ecosystems to climate change.

Forests are subject to a number of disturbances, such as insects, pathogens, wildfire, and wind. Climate variations may impact each of these. Because the available data (covering 1982—1995) for insect-caused tree mortality do not span a sufficient time period to allow analysis against 20th century climatic variability, our study has focused primarily on forest fire. A significant body of previous research has also examined the possible effects of climate change on fire regimes and forest ecosystems. For instance, several models simulating vegetation change under doubled CO_2 scenarios predicted that changes in fire regimes could significantly alter forest structure and species distribution patterns [39, 17, 104]. These findings are consistent with predictions for a number of regions within the greater Northwest. For instance, increased fire frequency and intensity have been predicted for the northern Rocky Mountains [139, 48] and for temperate and boreal forests in Canada [37]. Similarly, modeling work [154, 47] suggests that northern California will experience increases in the area burned annually and in the frequency of escaped fires. It is important to note, however, that the assumption of increased fire frequency and intensity with warmer, drier conditions may be overly simplified [1]. The uncertainty stems from the difficulty in predicting potential changes in other important factors that influence fire activity, such as wind direction, synoptic-scale sequences of weather events, and lightning activity [1, 2]. We have used a retrospective approach to determine whether relationships between historic forest fire activity and past climatic variability support predictions regarding future climatic change.

4.2.1 Relationship between forest fires and climatic variability

We have examined the connection between climatic variations and forest fire in the PNW during this century. ENSO and PDO directly influence PNW climate (as discussed on page 13), with warm phases increasing the likelihood that winter will be warmer and drier with lower snowpack and spring streamflow in snowmelt-driven rivers.

Forest fires were much more extensive in the PNW during the 1925—45 warm phase of PDO than during the cool phases before and after that (Figure 38; [108]). Some of the decline since 1945 can be explained by the rising use of fire suppression. The resurgence of fire activity in the late 1980's was consistent with the warm-dry phase of the PDO, but could also be explained by the cumulative effects of fire suppression. That these results are robust despite the changing fire suppression practices is suggested by a comparison with Figure 23, which shows that the 1925—45 period was unusually dry in the Columbia River Basin. The tendency for forest fires to occur in warm-phase PDO years holds true for each

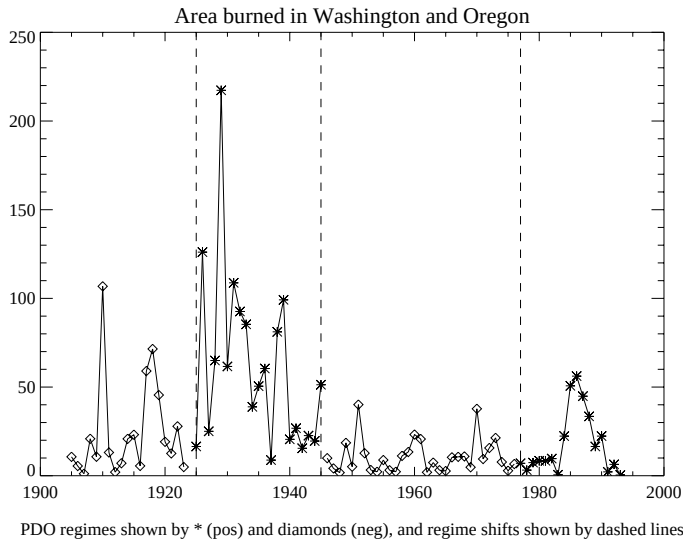

Figure 38. Annual area burned in forest fires.

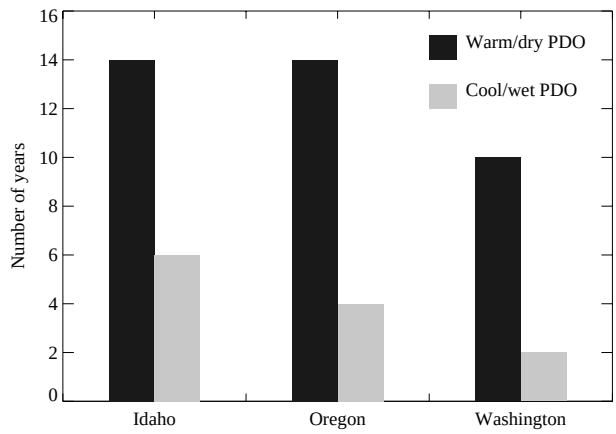

Figure 39. Number of years (1916—1997) in which area burned exceeded 200,000 acres, for warm/dry (black) and cool/wet (gray) phases of the Pacific Decadal Oscillation.

state as well (Figure 39). The differences in numbers of fires are statistically significant (at the 0.8 level for Idaho, the 0.95 level for Oregon, and the 0.925 level for Washington) for each state, using a *G*-test for goodness of fit with the Yates correction for continuity [164]. The PDO, by influencing forest fire activity, may thereby influence broader fluctuations in forest structure, composition, and function.

Forest fires show little relationship to ENSO, at least at the regional scale, suggesting that it is the accumulated moisture deficit of successive dry years, rather than dry conditions in a single year, that lead to extensive wildfires. The results are summarized in Table8, which shows the correlations between interannual time series (as in Figure 6) of ENSO, PDO, the Palmer Drought Severity Index (PDSI), and an index of area burned in Washington and Oregon (normalized by area monitored in each year). The PDSI, which estimates the accumulated soil moisture deficit or surplus from several months' temperature and precipitation, is influenced by ENSO and PDO, and in turn the PDSI is a fairly good measure of how extensive wildfires could be in a given year.

Although our analysis shows no relationship between area burned and ENSO (despite the connection between ENSO and PDSI), studies at a smaller geographic

ENSO	**0.39**	**0.21**	-0.05
	PDO	*0.28*	*0.24*
		PDSI	**-0.48**
			burned area

Table 8. Correlation of ENSO and PDO with the PDSI and area burned by wildfire in Washington and Oregon. Statistically significant relationships are indicated by boldface (95% or higher) or italics (80% or higher).

scale may show a linkage between ENSO and wildfire; for example, such a link has been shown for certain watersheds in the Blue Mountains of eastern Oregon [67]. The lack of relationship between ENSO and wildfire in the PNW stands in marked contrast to the strong relationship between ENSO and wildfire established in the southwestern United States[147]; one difference is clearly the important role of ENSO in creating greater fuel accumulations during positive phases of ENSO in that region, an effect that is not relevant under the high fuel loadings always present in forests in the PNW.

4.2.2 The importance of synoptic-scale fire weather}

A critical factor to weigh in analyses of climatic variability and fire activity is the occurrence of certain sequences of synoptic-scale (i.e., regional-scale) weather events associated with fire outbreak and spread. These "fire weather" sequences occur randomly, even during otherwise wet years, and therefore there is only a weak connection between years with many large fires and seasonal-scale climate variations like those associated with ENSO and PDO.

A number of studies have described a synoptic-scale sequence of weather events leading to lightning-caused ignition and fire spread. This sequence of weather events has been described for boreal forests in Canada [79, 76], coastal temperate coniferous forests in the Pacific Northwest [70, 130]; ponderosa pine forests in the Southwest [147]; and for the entire United States by sub-region [66]. The sequence begins with the development of a high-pressure upper-level ridge, also known as a blocking high pressure system. The high pressure system may last a month or more, during which time precipitation and humidity are low, temperatures are high, and winds are light. These conditions leave fuels dry and vegetation under severe water stress. When the high pressure system either partially or fully breaks down, convective storms can lead to lightning-caused ignition which, when combined with higher wind speeds, can lead to fire spread through the now flammable fuels.

'Schroeder *et al.* (1962) [141] investigated fire weather and found that, in the Pacific Northwest, the period of highest risk of wildfire caused by synoptic weather events runs from June through September, with occasional critical periods as early as April and as late as November. Two types of surface air flow systems with off-shore (easterly) components were described that increased fire ignitions: Pacific Highs and Northwest Canadian highs. Schroeder *et al.* [141] state that:

> Flow from this direction [the East] not only keeps the marine air offshore but also results in adiabatic warming. If a portion of a Pacific or Northwest Canadian High moves into the area east of the Cascades, easterly winds are found in the region between this area and a trough along the Pacific Northwest coast, and high fire danger occurs west of the Cascades.

Other work also points to the importance of east wind [2] and to the existence of two main types of circulation systems leading to fire weather [66].

Because of the importance of synoptic-scale weather to forest-fire occurrence, models that simulate vegetation change are beginning to incorporate a random component that approximates fire weather [90].

4.3 Possible future changes and the impacts of climate change

In this section we review the important factors controlling how forests might respond to climate change. We also review numerical models of forest ecosystem change under climate change scenarios, including recent modeling work done as part of the National Assessment (see Appendix E).

4.3.1 Climatic factors influencing forest ecosystem change

The impact of climatic change on the forests of the PNW can be considered in terms of both direct and indirect effects as described in section 4.2. Certainly some direct effects are predictable from the physiological effects of increased moisture stress, increased temperature, and increased CO2 levels in the atmosphere although we have not attempted to quantify them. Increases in summer temperature without substantial increases in rainfall, as predicted in most current climate change scenarios for the PNW (Figures 13, 14), would result in **greater potential evapo-transpiration and decreased soil moisture** [60].

Increased moisture deficits during the summer will result in increased plant moisture stress, reduced net

photosynthesis, reduced growth, and increased overall plant stress. Increased temperatures will also increase respiration rates. Although a positive CO_2 fertilization effect is sometimes predicted, the effects of increased CO_2 levels on productivity are very uncertain due to the highly interactive nature of the CO_2 response with other environmental and physiological factors, partially explaining the extremely varied results found around the world [158]. Furthermore, cool-climate conifers are viewed as least likely to show a positive response to elevated
CO_2 levels [158, 6].

Reductions in snow cover could have a variety of effects, some positive and some negative [127]. Different climatic zones have different limiting factors. In areas of deep snow (the western slope of the Cascade Range, Olympic Mountains, and high elevations in the interior mountain ranges), a reduction in snowpack lengthens the growing season, giving tree seedlings a better chance at establishment [127]. In dry areas (the eastern slopes of the Cascade Range, the Blue and Wallowa Mountains, and moderate elevations of the Rocky Mountains in Idaho and western Montana), soil moisture is a limiting factor and reductions in snowpack would reduce the amount of moisture available at the beginning of the growing season and increase the length of the late summer drought period; both conditions would make it more difficult for seedlings to establish themselves.

The ponderosa pine and mixed conifer forests east of the crest of the
Cascade Range are probably more vulnerable to these changes in climate simply because the climate there is already so dry. Further increases in evapotranspiration will probably have a bigger impact there than in the wetter forests west of the crest of the Cascade Range. However, some detrimental impacts of increased moisture deficits can be expected in west-side forests, such as increased fire hazard and levels of physiological stress in trees and forest stands.

In summary, **the net direct effect of the climatic changes is not likely to be favorable** to the productivity and stability of existing forests. Warmer summers, leading to increased evapotranspiration, are likely to overwhelm any benefits of increased CO_2 fertilization [33].

Indirect effects, chiefly through changes in forest fire characteristics, are likely to be even more important than these direct effects. Predicted climatic changes are likely to have profound and, relative to plant responses, immediate and easily observed impacts on disturbance regimes. This is most obvious in the case of fire where increased summer temperatures and moisture deficits will substantially increase the potential for the occurrence, intensity, and extent of wildfires. Changes in other types of disturbances, such as from wind, insects, and disease, are also possible [46].

Effects of climate change on forest insect pests and pathogens depend very much upon whether there are increases or decreases in summer precipitation. If summer precipitation remains the same or decreases, the effect, along with increased temperature, will be more physiological stress on trees due to summer drought with consequent increases in potential susceptibility to insect attack [97]. If summer precipitation increases enough to compensate for the impact of increased summer temperatures on moisture stress, susceptibility of insect attack could remain the same or decrease for at least the short term. Eventually, increases in winter temperature could allow some insect pests and diseases to survive and reproduce more effectively.

Wind storms are another disturbance that damages or destroys trees. Climate models are not yet adequate to suggest whether such storms will increase or decrease, but in past climate variations, wetter winters have had more wind storms (N. Bond, personal communication, 1999). Given that nearly all climate model scenarios suggest an increase in winter precipitation in the Northwest, it seems reasonable to infer an increase in winter wind storms, and possibly an increase in frequency and intensity of wind damage to forests.

The predicted increases in extent and intensity of wildfires and other disturbances are likely to result in abrupt or rapid shifts in forest distribution. This will be especially noticeable at ecotones, such as the semi-arid, low elevation forest-lines which are transition zones grasslands and forests [3].
Since environmental conditions are already near the margins for trees and forests at such locations, these ecotones are particularly sensitive to climatic influences.

One expected effect of current climate scenarios is for a significant reduction in forested area in both the moist western and arid eastern sides of the Cascade Range (Figure 40) [46]. These changes in forest areas are likely to be brought about by wildfires; without such disturbances changes in forest composition and functions would probably be much more gradual. In addition to a potential net loss of forest land, there will be net increases in grasslands, shrublands, and savanna and very significant reductions in “snow zone” communities, such as mountain hemlock forest and alpine and subalpine meadows.

As a result of all these changes, forest communities are expected to undergo major shifts in their species composition. Species range shifts are expected to be very individualistic rather than primarily as collections of currently associated species. Extinctions of local populations and even species are expected. Spatially explicit or site-specific predictions regarding potential vegetation change will continue to be highly uncertain, however, because of the complex interactions between physical template, or geomorphic diversity across different spatial scales, and climate change [18].

4.3.2 Changes in PNW vegetation predicted by vegetation models

Quantitative or spatially explicit predictions of potential future changes in vegetation distribution and composition are fraught with uncertainty. For the PNW, empirical or process-based models have produced highly contrasting predictions regarding changes in forest distribution with regards to both magnitude and direction of future changes (e.g., forest dieback versus forest expansion). These disparities stem from differences in model assumptions regarding several critical parameters, including effects of precipitation increases and of elevated atmospheric CO_2 on physiological processes, such as plant water use efficiency. By understanding the key parameters driving forest responses in the Pacific Northwest we can formulate alternate scenarios of future forest ecosystem change.

An early assessment [46] of likely forest response to climate change used empirical, correlation modeling to relate potential shifts in mean annual temperature to forest community gradients or life zone classifications for the Pacific Northwest [43]. A key aspect of the approach used was that no change in water use efficiency (WUE) or tree productivity due to CO_2 enrichment was assumed. Franklin *em et al.* [46] estimated potential shifts in forest community types along elevational and temperature gradients, but recognized that the paleobotanical record for the Pacific Northwest [26, 27, 28, 18] and physiological considerations [91] make it likely that actual vegetation shifts will occur as a function of individualistic species' responses. These independent shifts by individual species, rather than shifts of intact plant communities, will probably result in species assemblages not currently found on the landscape. Under a scenario of increased mean annual temperature, which resulted in an increase in summer soil moisture deficits at lower and middle elevations, Franklin *et al.* [46] predicted a net decline in forested area in the Pacific Northwest. Especially pronounced forest dieback and commensurate expansion of sagebrush-steppe communities were predicted at drought-sensitive lower treelines on the eastern slopes of the Cascade Mountains (Figure 40). Changes in vegetation distribution are likely to show tremendous fine-scale variation due to topographic and environmental heterogeneity on fine scales [18]. The predictions of Franklin *et al.* [46]should be applied only at coarse scales.

Another more recent study (Neilson and Drapek, 1998 [115]) used a physiological process-based model to predict vegetation change both globally and for the conterminous United States. Neilson and Drapek used the Mapped Atmosphere-Plant-Soil System equilibrium biogeography model [114] to examine biosphere responses to two more recent and several older GCM scenarios. On-going work has linked the MAPPS model with MCFIRE, a broad-scale fire severity model [90] and the CENTURY biogeochemical model [122, 123] in an effort to built a Dynamic Global Vegetation Model, called MC1, that incorporates disturbance processes and related feedbacks. One significant problem with MC1 is that it inaccurately predicts current vegetation for large portions of the Pacific Northwest. MC1 classifies the majority of land area west of the Cascades in Washington and northeastern Oregon as deciduous forest (Figure 41), when, in fact, coniferous evergreen forests dominate. The inability to correctly predict current vegetation lowers our confidence in the model's ability to predict future vegetation distribution. One reason for MC1's inability to predict current vegetation may be its failure to adequately incorporate the critical regional climatic parameter summer drought or moisture deficits. Other models (e.g. VEMAP) also weigh increases in frost-free or growing season as an important factor favoring forest development under global warming. Frost-free period or length of growing season is generally not an important variable controlling productivity in western coniferous forests [160].

Several of the scenarios simulated in Neilson and Drapek's [115] models runs show significant future expansion of the area occupied by temperate evergreen and temperate mixed forest classes. This trend holds both for the U.S. as a whole and for the Pacific Northwest region. These results, which are really only a subset of

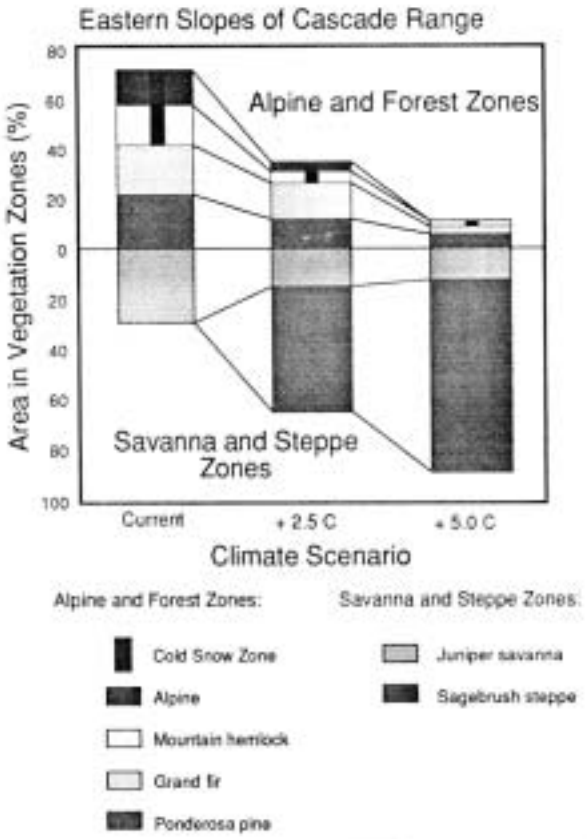

Figure 40. Area occupied by various plant types and the changes expected under a warming climate. From [46].

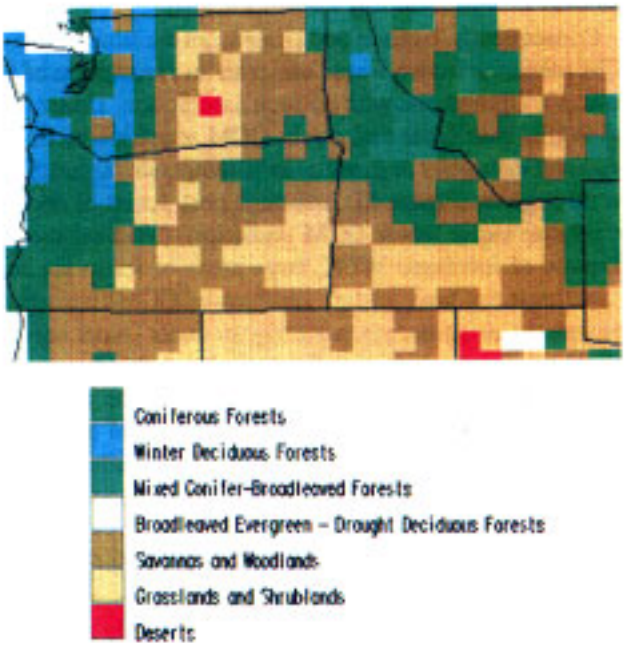

Figure 41. Present distribution of major plant types in the PNW as simulated by the MC1 model.

Neilson and Drapek's results, appear to differ from the earlier results of forest dieback. Their results of forest expansion rest on two very important — and contestable — assumptions.

Direct effects of CO_2 enrichment The first assumption is that elevated CO_2 will cause changes in water use efficiency (WUE), such that the model reduces maximum stomatal conductance by 35% [115]. Elevated CO_2 has been shown to increase WUE in some laboratory studies ([6, 83], cited by [115]). However, as Neilson and Drapek point out, there are a number of physiological feedback mechanisms and effects of increased air temperature that may cause forests to experience no increase or only a short-term increase in WUE and related productivity [6, 87]. Scenarios showing CO_2-related forest expansion are thus likely to be short-term or transient only [115].

Consequently, Neilson and Drapek ran the simulations of GCM scenarios in two ways: one with an assumption of increased WUE and one with no such assumption. Under normal WUE, both older and newer GCM scenarios produced *consistent decreases in forest area* in temperate latitudes below 50 degrees (Figure 42), although peak levels of decline were lower under newer GCM scenarios. "Without the assumption of increased WUE, large areas of forest are lost to nonforest for both [older] and [newer GCM] scenarios, although the magnitude is much higher under [older scenarios]" [115]. When no direct effects of elevated CO_2 are considered, forests decline along dry, low elevation ecotones, resulting in a contraction of temperate forests in dry continental interiors like the east slopes of the Cascades. These findings are completely consistent with those shown in Figure 40.

The key question, then, is: Will Northwestern forests experience enhanced water use efficiency? At present, the balance of evidence suggests that there will be little or no enhanced WUE and primary productivity in forests experiencing elevated CO_2 [6, 117, 33]. Only limited data are available on forest responses to elevated CO_2 under field conditions [117], and no such studies have been conducted in forests in the Pacific Northwest. However, Free Air CO_2 Enrichment experiments in pine forests in North Carolina found no evidence of enhanced WUE in elevated CO_2 plots compared to ambient plots under either drought or non-drought conditions [33]; however, drought conditions were found be an important predictor of forest productivity (Ellsworth 1999). This suggests that climatic changes resulting in increased soil moisture deficits during the growing season will cause forest productivity to decline, even with elevated CO_2. The seasonal distribution and amount of precipitation, consequently, become critical parameters to consider in climate change scenarios and vegetation change modeling. In evaluating vegetation change scenarios, it will continue to be appropriate to consider scenarios both with and without enhanced forest productivity due to elevated CO_2.

Precipitation and summer drought The second assumption concerns the relative importance of winter and summer precipitation. Past studies have shown the overwhelming importance of the summer drought and extreme plant moisture stress on the distribution of tree species and productivity of forest ecosystems in the Pacific Northwest [165, 57, 160, 55, 89]. It is highly likely, therefore, that climatic changes which 1) increase the length of the summer moisture deficit, 2) increase the intensity of the summer moisture deficit, or 3) increase the frequency of multiple summer droughts—or any combination of the three—will result in a reduction in forest cover and biomass and in loss of species at the dry end of their ranges. The effects of these types of changes are, furthermore, likely to operate through several mechanisms. These include: 1) direct impacts on the physiology, vigor, and mortality rates of established trees, 2) increased probability of and intensity of fire disturbances which kill established trees and forests, and 3) increased difficulty, for some species, of tree regeneration and establishment on open areas. Consequently, **even with increased total annual precipitation or increased WUE, any climatic changes (such as reduced summer precipitation or increased summer temperature) that result in a net increase in soil and plant moisture deficits are likely to result in increased physiological stress and reduced productivity** [33, 89]. It is critical, therefore, to examine modeling assumptions that affect how summer soil moisture deficits are calculated in simulations of future vegetation change.

The MAPPS model developed by Neilson and Drapek [115] simulates changes in plant community distribution by estimating potential leaf area index (LAI). LAI calculations in the model are based on the physiology of stomata and tree rooting depths [114]. Model estimates of LAI for forest ecosystems are highly sensitive to reduced summer precipitation and increased summer temperature.

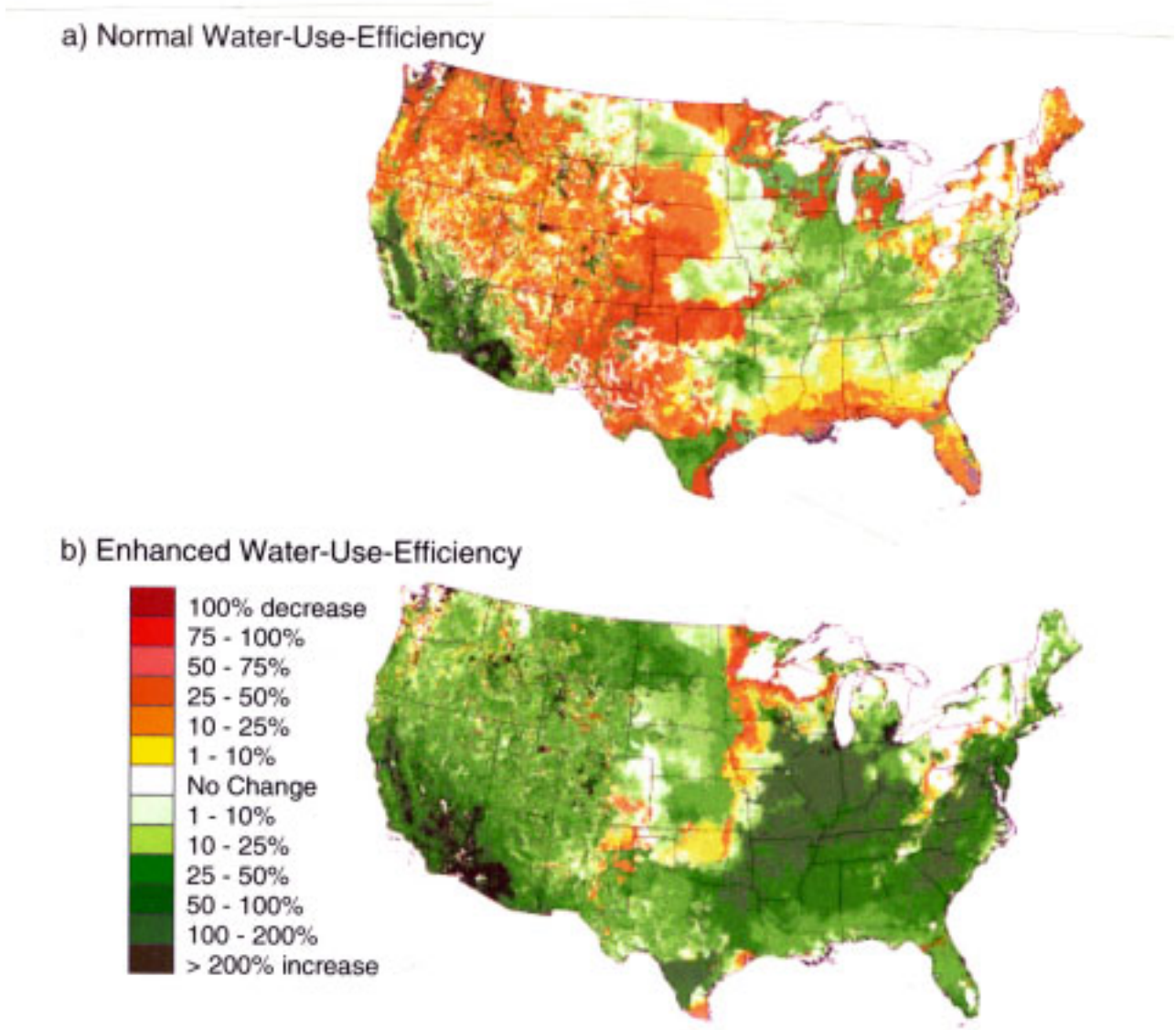

Figure 42. Changes in leaf-area index (LAI), a measure of forest density, simulated by the MAPSS model under the HC scenario with assumptions of (top) no enhancement in water use efficiency (WUE) and (bottom) enhanced WUE. Green colors show increases in LAI and brown colors show decreases.

It is the addition of an assumed increase in water-use-efficiency that counter-balances the otherwise increased susceptibility to summer drought stress. In addition, the model assumes that increases in winter precipitation will result in increased soil moisture recharge, thereby compensating for reduced summer precipitation and increased temperatures. With little summer precipitation in any of the climate change scenarios evaluated, evapotranspitative demand during the growing season is met by deep ground water charged by winter rains and snowmelt. This is an important assumption that warrants careful evaluation.

For the PNW, there are indications that, at coarse spatial resolution and below the snowline, **the soil is fully recharged under current winter rainfall, so increases in winter rainfall would only increase immediate runoff** [64, 126, 80]. No further increase in soil water storage with increased winter rains is therefore possible in the Pacific Northwest. Increases in winter rainfall will most likely result only in increased runoff and will not alleviate summer moisture deficits. A very probable effect of increased winter temperatures is reductions in depth of snowpack. These are likely to reduce soil water recharge during summer months in mountainous regions. The MAPPS model uses a generalized soils model that does not incorporate the lack of additional or surplus winter soil water storage capacity in the Pacific Northwest. Consequently, there is little or no basis for the model assumption that increases in winter precipitation will reduce summer soil deficits will decrease in the Pacific Northwest. Under a scenario of decreased summer precipitation it is not likely, therefore, that drought stress will decrease and that forested communities will expand into areas currently occupied by grassland, shrub-steppe, or drier and less productive forest types or savannas.

Summary: scenarios of forest ecosystem change in the Pacific Northwest A number of different climate change scenarios have been generated for the Pacific Northwest (see section 1.2). For most, winter precipitation increases; summer precipitation either decreases or increases. Increases in winter temperature result in decreased snowpack, such that more precipitation falls as rain and less as snow. And with no further increase in soil moisture storage possible, the net result is increased runoff with reduced summer soil moisture availability. Some scenarios predict modest increases in summer precipitation, resulting in reduced soil moisture deficits. Because of the disparities between these scenarios, it is not possible at this time to generate only one scenario of possible forest change in the Pacific Northwest. Instead, we must construct two scenarios based on variable precipitation and temperature regimes.

Scenario 1: Summer soil moisture deficits increase due to increased summer temperatures and no increase in summer precipitation.

Forests decline due to the combined effects of increased drought stress in established stands, increased probability of insect and fire disturbance, and reduced seedling survival. Forest decline will be particularly pronounced at low elevation interfaces between forested and non-forested plant communities on the eastside of the Cascade Range and in the interior Northwest [46, 115].

Scenario 2: Reduced summer soil moisture deficits due to increased summer precipitation

Forests expand into areas in the dry, interior Northwest currently dominated by grassland and shrub-steppe communities [115]. If summer temperatures increase sufficiently over the long-term, resulting in a net increase in evapotranspitative demands, forest dieback may occur in both colonized areas and currently forested areas despite the increase in summer precipitation.

4.4 Socioeconomic impacts of the likely changes

These physical and biological changes in forests can be expected to have a variety of socioeconomic consequences for the PNW, most of them negative. Climate changes are predicted to result in major changes in the production of goods and services from the forests of the PNW. Reductions in the average productivity of the forest lands can be expected under increased summer moisture stress along with the significant net reductions in forest area. Declines in forest productivity in some areas could lead to a decline in long-term timber yields which would affect the region's economy. Higher timber prices and reduced availability of wood fiber could also affect other industries and sectors although these changes could be mitigated by increased imports of wood products from other regions. Such mitigation of economic impacts would obviously depend upon how forested areas in other regions around the world fare in relation to climate change.

Several other **consequences of reduced forest cover** include reductions in water quality, air quality, and carbon sequestration (storage of carbon). Forests serve to regulate water flow both above and below ground. A reduction in forested area would increase the frequency and intensity of flood events and decrease production of clean water for human consumption and recreation. In addition, forest streams provide quality habitat for fish (e.g., for salmon spawning and rearing); this function would also be impaired by a reduction in forested area. If forest

fires become more widespread (at least for a period of time while forests are shifted to nonforest cover), adverse on air quality and public health can be expected. The diminishment of productivity along with increased frequency of wildfire will result in a net flux of carbon from that sequestered in current organic matter stores to the atmosphere; in other words, the overall carbon sequestering capacity of the forests of the PNW will be significantly reduced. Increased frequency of high intensity fire could result in increased rates of carbon cycling with a net gain in atmospheric carbon (Neilson *et al.* 1994; Sohngen *et al.* 1998). This would create a positive feedback loop, exacerbating rates of global climate change and related rates of forest ecosystem change.

4.5 Coping options for resource managers

Forests, more than most of the other resources considered in this study, are sensitive to climate primarily on long time scales. Trees planted now are likely to mature in a different climate from the one we have today. Although trees are most vulnerable to climate extremes as seedlings, forest growth is affected by climate and it would be in the best interests of foresters when replanting a logged area to consider carefully the choice of species. It may be that the greatest growth potential could be achieved with a species that is presently uncommon in that area.

The development of strategies for coping with climate variability and future climate change first requires recognition of the vulnerabilities caused by such climate variations. The sensitivity of the PNW's water resources to current climate variability is evident within the region, due mostly to conflicts over water in low-flow years, and presages vulnerability under future climate change. Based on interviews we have conducted, however, forest managers generally do not consider forests to be sensitive to climate variability. The averaging of climate conditions over a tree's lifetime (15—1000 years) or even over a 40—70 year forest harvest rotation, tends to obscure the effects of seasonal and interannual climate variability. Mature trees tend to be resilient and therefore less sensitive to climate variability or change. Thus **climate variability is generally not considered** within forestry management planning and decision-making. This stands in contrast to the previous two sectors we discussed (water resources and salmon), in which at least some limited consideration is given to interannual variations.

In forestry, therefore, a whole mindset needs to be changed. An encouraging first step in this direction is the recent decision by the Commissioner of Public Lands in Washington State to explore how to incorporate climate change into long-range planning, with a view to plan the management of our natural resources with the best information available (R. Stender, personal communication, 1999). Otherwise, however, the information on climate variability and change has yet to penetrate into forest management.

In the analysis conducted by the CIG, what lessons have we learned that may be of use to managers?

- The impacts of climate variability and change are most likely to be felt at the edges of forests' physical extent, of the lifespan of trees and of conditions.

- It is during the stage of tree regeneration, or seedling establishment, that forests are most vulnerable to climatic conditions. Seedlings are especially sensitive to temperature extremes and to drought, and seedlings of a certain species may not be able to establish and grow under changed climate conditions in certain locations where mature trees of that species now grow.

- The increased frequency of multiyear droughts when ENSO and PDO are in phase, and the projections of increased frequency of summer drought in future, indicates potential difficulty for forest regeneration during these times. If seeding and planting to not succeed, the costs of replanting and of foregone production could be significant.

Climatic variations influence forest conditions through changes in the frequency or character of forest disturbances. Forest fire activity seems to increase during the warm phase of the PDO, and the climate changes projected by the models (warmer summers, earlier snowmelt) suggest by analogy that the potential for fires is likely to increase substantially. Clearly, climate variability on decadal timescales is important to forests, but our interviews suggest that it is not taken into account by forest managers. If the future calls for the increased frequency and severity of summer drought, which imply an increased probability of high intensity wildfires, does this then portend rapid shifts in forest compositions as a combined effect of both fire and summer drought relative to seedlings and therefore the rate of forest regeneration? And does the strength of the decadal

signal imply that managers should choose species in order to trade growth for survival under climate change scenarios?

These issues would appear to be responsive to sustained programs of education conducted by a regional climate service with a highly integrated information capacity. A regional climate service would disseminate not only climate forecasts but state of the art information about the links between climate variability and forest establishment, growth, persistence and disturbance regimes. How do ENSO and PDO affect potential evapotranspiration and what does this imply for summertime moisture stress and seedling viability? What does the current phase of the PDO imply for the scope of prescribed burning required to mitigate large-scale wild fires? The understanding of the relationships between climate variability and forests would provide the basis for management decision making in the context of global climate change. What species should be planted now to ensure forest viability throughout the next 70 years? **What must we do to ensure that the forests in our national parks and wilderness areas are maintained as the climate changes?**

In the face of this complexity, what can we recommend as coping strategies? The group of forest managers and academics who participated in the summer 1997 Workshop (see Section 2.1 of Part I) agreed on a suite of actions to recommend as coping strategies. These included:

- Need for a new approach to forestry management: Develop ability to plan and implement at longer time and larger spatial scales in decision rules for forest management.

- Ways of dealing with uncertainty:

  – Maintain full range of biological diversity (including species, population, and genetic diversity).

  – Design reserves and protected areas to incorporate the maximum geomorphic or landscape diversity possible [18].

  – Maintain the complexity of forest structure and composition within intensively managed areas.

- Management options:

  – Manage forest density for reduced susceptibility to drought stress.

  – Plant species with known broad physiological climate response curves.

  – Adapt tree planting to reflect changes in summer growing conditions, for example, transition to planting of Douglas fir on appropriate sites in the silver fir zone.

  – Use prescribed fire to reduce susceptibility to high-intensity, large disturbances.

  – Develop management systems to provide for more retention of sequestered carbon.

- Informed decision making:

  – Actively monitor trends in forest conditions and climate related stress/changes in general and with regards to different systems of silvicultural management (internationally).

  – Actively disseminate this information to forest managers and policymakers.

Based on what we now know about the impacts of climate variability on forests, we offer some additional advice. It is important to recognize the vulnerability of forest establishment to interdecadal climate variability, in order to avoid seeding and planting failures and the associated costs of replanting and delayed stand maturity. Managers should use climate forecasts and an understanding of the influences of ENSO and PDO to predict the likelihood of wildfire and to plan the timing of prescribed burning in drier-than-normal years. Managers should also seek to understand, on the very large spatial scale for which seasonal forecasts are valid, the relationships between disturbance regimes and climate variability, in order to try to limit adverse effects.

In a highly integrated fashion, then, a regional climate service would provide information about both climate and its multitudinous links to forest management to those making management decisions. The result would be better informed and therefore adaptive management of all types of forested land—whether they be managed for timber production, habitat preservation or carbon sequestration.

Coastal Zones

The Pacific Northwest has three distinct "coasts": the shores of the inland marine waters of Puget Sound and the Strait of Juan de Fuca (3,614 km); the Pacific Ocean coast itself (859 km total, 275 km in Washington and 584 km in Oregon); and the shores of the estuaries fronting the Pacific Ocean (2773 km total; 504 km in Washington and 2269 km in Oregon)[1]. In our initial assessment, we considered several aspects of the consequences of climate variability and change on the coasts of the PNW, focusing on the physical landscape, which is affected by:

- coastal erosion
- landslides
- flooding
- inundation

In addition, redistribution of sand and sediments lead to beach-building or beach erosion in some places. Aquifers may be affected by sea water intrusion. Ecosystems may be affected by the growth or shrinkage of wetlands, and by the invasion of exotic species.

5.1 Current status and stresses

The coast of Puget Sound includes the most intensively developed marine shorelines in the region (e.g., the rapidly growing Tacoma-Seattle-Everett metropolitan complex) as well as expensive bluff-top or beach-front trophy homes, suburban areas, and remnants of agricultural and timber-growing tracts. Here, storm and wave energy regimes are tempered by Puget Sound's inland location. Puget Sound shorelines are predominantly narrow beaches, fully or mostly inundated at high tides, and backed by steep banks or bluffs; sand spits are few and small; rocky shores are common only in the San Juan Islands of north Puget Sound. Substantial portions of the central and south Puget Sound shoreline have been armored in urban areas, at shoreline railroad fills, and for shoreline residential development.

The Pacific Ocean coast, by contrast, has relatively lower intensity development: there is no major urban center; significant portions of the coast are public parks or other reservation, or within the bounds of Indian reservations; development occurs only in limited areas along the coast. Here, the coast is open to the full force of storm-driven waves. Washington's north Pacific coast is characterized by steep, rocky bluffs and headlands, punctuated by a few small pocket beaches, with land ownership predominantly within the Olympic National Park and five Indian reservations. Washington's south Pacific coast is characterized by broad sandy beaches and sandspits acting as "barrier islands" at the mouths of Willapa Bay and Grays Harbor; land ownership is mostly small residential parcels and lots. Oregon's Pacific coast is characterized by steep, rocky bluffs and headlands, punctuated by pocket beaches and bay mouth sandspits; land ownership is mostly small residential parcels and larger undeveloped holdings. Here, up-scale and expensive vacation homes, condominiums, and destination resorts are often built dangerously close to erosion-prone shores or the edges of unstable bluffs. The shallow coastal estuaries are characterized by small cities and towns at the river mouths, still-extensive farm-lands and dairy-lands, and shellfish aquaculture.

[1]Marine shorelines are fractals, and therefore length data vary depending on the scale of mapping used for the measurements. For Washington State, the tabulation by Hagan [58] based on 1:20,000 to 1:200,000 mapping was used. For Oregon, coastal data were taken from [40], based on 1:24,000 mapping; the source, however, of estuarine shoreline length is uncertain.

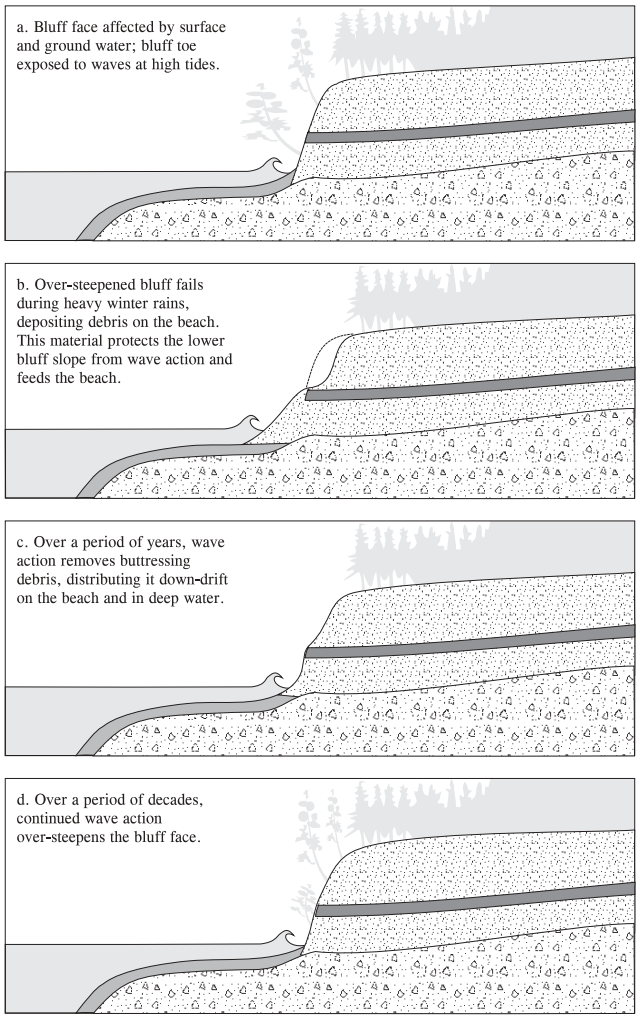

Figure 43. Evolution of Puget Sound bluffs.

Coastal erosion, or more accurately, shoreline retreat, may be due to beach erosion alone on unconsolidated (loose) shores, or to a cyclic combination of beach erosion and bluff landsliding on bluff-backed shores (see Figure 43, [22]). Beach erosion is associated with winter storm waves and in many places has a normal annual cycle with sand accumulating at one end of a littoral cell (a section of beach with its own local circulation of water and sand) during the winter and returning to the other end of the littoral cell in summer, with a net drift to the north on the Pacific coast.

Bluff **landsliding**, which occurs primarily in the glacially deposited steep hillsides around Puget Sound, is associated with heavy winter rainfall [50]. It may depend on a variety of factors in a given location, including the timing and intensity of rainfall, the local geological characteristics, and the recent history of landslides.

Coastal flooding is an episodic, localized problem. It occurs primarily at the mouths of major rivers when a flood flow reaches the coast on a high tide. Most coastal urban areas are protected by upstream flood control reservoirs or were developed with enough freeboard to protect against flooding. Some urban areas, e.g. Olympia (Deschutes River mouth on south Puget Sound), Aberdeen (Chehalis River mouth on Grays Harbor), or Raymond (Willapa River mouth on Willapa Bay), lack both flood control reservoirs and freeboard, and thus are subject to periodic flooding. Agricultural districts in river deltas are typically protected by dikes; occasionally, high river flows on a high tide result in breaches of the dikes and flooding (e.g., Fir Island in the Skagit River mouth on north Puget Sound).

Coastal **inundation**, unlike flooding, is a gradual process in response to both global and local factors. Eustatic sea level rise (i.e., sea level rise produced by global factors like warming of the oceans and melting of landlocked ice) acts in combination with local vertical land movement and fluctuations in sea level associated with regional ocean conditions. During this century, global sea level has risen 1—2.5 mm/yr [72]. The combined effects of eustatic sea level rise, local land movement, and local beach slope will be discussed in section5.3 for several locations in the Pacific Northwest.

Sea water **intrusion** is a localized problem, mostly where operation of extensive private well fields leads to over-drafting of coastal aquifers. Most known instances lie within the developing Puget Sound urban-suburban subregion.

Threats to coastal ecosystems include the loss of wetlands to erosion and the invasion of exotic species such as Cordgrass (*Spartina* spp) or the European Green Crab (*Carcinus maenas*). The rapid spread of Cordgrass in Willapa Bay, beginning in the 1980s, threatens to transform the bay's extensive mudflats and eliminate most commercial oysterbeds. The green crab could have substantial negative impacts on local commercial and recreational fisheries by preying on the young of valuable species (such as oysters and Dungeness crab) or competing with them for resources. The combined effects of Cordgrass and the green crab are unknown.

5.2 Past changes and the impacts of climate variability

Much of what we know about the impacts of climate on the coasts of Washington and Oregon have come from three major studies. In the late 1980s and early 1990s, the Washington Department of Ecology completed or funded technical and policy projects focused on sea level rise in Puget Sound (e.g., [21, 84, 24]). A prematurely-terminated US Environmental Protection Agency regional study focused on inundation of marine wetlands of Washington State [121]. Finally, the JISAO/SMA climate impacts study has broadened the geographic scope to include the Oregon coast, and has also broadened the topical scope [36, 78].

There are few long-term measurements to assess the impacts upon coastal systems of climatic variations, but there are several pieces of information we do have. We know that El Niño events tend to raise sea level along the west coast of the U.S. for several months and change the direction from which waves arrive; both factors tend to increase coastal erosion on the Pacific Ocean coast. The open coast of Oregon and Washington is subject to severe ocean storm surges and resulting erosion events about every five years on average. Significant erosion causes inlets to migrate and lagoons to fill. Erosion washes away former sedimentary deposits and often undermines shore protection works. The southwest Washington coast now suffers net loss of coastal lands, reversing a long trend of sediment build-up. In Ocean Shores, Washington, recent storm waves have caused erosion around the flanks of an armored beach fill that was placed to protect condominium developments. An Oregon study [51] showed that the length of shore protection works constructed in the Siletz littoral cell increased dramatically in the years immediately after a severe El Niño event. These examples illustrate diverse human responses to climate variability and suggest that greater pressure will be exerted to armor shorelines in the future.

We also know that La Niña events tend to increase winter rainfall, which in turn increases soil saturation and therefore landsliding [156]. This is typified by the minor La Niña of 1996—97 [50], which resulted in considerable damage from landslides (Figure 44), and the major La Niña of 1998—99. Significant numbers of landslides in the Seattle area have occurred during the winters of 1933—34, 1985—86, 1996—97, and 1998—99; all were La Niña winters, and all but 1985—86 were exceptionally wet winters. The link to the PDO appears to be more complex: the average number of landslides appears to be higher in the cool-wet phase of the PDO, but of the winters just mentioned with large numbers of landslides, the first two occurred in the warm-dry phase of the PDO. If the PDO has shifted to a cool-wet phase (see section 1.1.2), then perhaps the average winter would see a higher number of landslides.

Figure 44. Hillside in Seattle overlooking Puget Sound, where several houses slid during the wet La Niña winter of 1996—97. Photo courtesy of the Washington Department of Ecology.

Recent research sponsored through the JISAO/SMA CIG has focused on three locations in the PNW region where climate variability and change are likely to have the greatest impact on coastal resources. The first is southern Puget Sound where low-lying areas and coastal settlements already endure greater risks of storm inundation. This is an area where land subsidence creates the greatest relative sea level rise in the region [21. 145]. The second is the southwest Washington and Oregon coastal region, which suffers from severe ocean storms and rapid sediment erosion and redistribution, and is also affected by a long-term decline in the volume of sediment

supplied by the Columbia River as a result of the construction of dams. Finally, estuarine areas in southwest Washington State, which serve as important habitat for marine living resources, can suffer shifts in the type and extent of living resources due to climate-induced physical and chemical change.

As with coastal erosion, inundation too is more common during El Niño events because sea level tends to be higher than normal, by 5—10 cm in central and southern Puget Sound. As noted above these areas already are subject to inundation during storms. Above-normal tides due to climate variations such as El Niño can combine with storm conditions to cause extreme inundation. Knowledge of this vulnerability should stimulate a review of policies concerning shoreline setback zoning, shore construction standards, infrastructure improvements, evacuation and emergency planning, and—in the long term—retreat from certain coastal areas. Studies of potential inundation done for Olympia, Washington [24] now need updating with the new information about sea level increases related to climate variability.

Physical change from tides and storms is only one effect of climate variability and change. In addition, biological effects are felt in estuaries because of the physical and chemical changes experienced. Studies of Willapa Bay in southwest Washington, where there are extensive tideflats and a large oyster industry, show a fairly steady decline in the Oyster Condition Index (OCI) over the 45 years it has been followed. The OCI measures the amount of oyster meat in the shell. Numerous explanations are offered for this observed decline. For example, interdecadal climate variability associated with the Pacific Decadal Oscillation (see Section 1.1.2) could explain why the OCI was above average in the decades prior to 1977 but declined to below average after that time. In these interdecadal phases, lasting about twenty years each, factors of primary production, whether marine or riverine, vary and could explain the differences in the OCI. Another explanation is that the OCI is declining monotonically due to habitat changes in the watershed, changes in Columbia River flow and water quality, or water pollution problems in the Bay. Further hypotheses relate phytoplankton biomass and oyster production. Declines in plankton populations can adversely affect oyster growth but there is scant information about plankton in the area that exchanges with Willapa Bay.

Climate may be a factor in the spread of some exotic species. Cordgrass, first introduced to Willapa Bay in the 1890s from Chesapeake Bay, first gained momentum only during the warm decade of the 1980s. Summers are typically shorter and cooler in western Washington than in Maryland, and the fact that a warm decade coincided with rapid growth may suggest climate-related causality, but such a link remains purely speculative. Recent work [35] suggests a link on a year-to-year time scale between a particular sequence of climate variations and the rate of spread of cordgrass. Unlike Cordgrass, the European Green Crab has broad climatic tolerance, and climate is likely not a factor in its spread north from San Francisco Bay.

5.3 Possible future changes and the impacts of climate change

The long-term effects of climate change on the coastal zone will likely be similar in nature, and greater in magnitude, to the effects of short-term climate variability. Several relevant factors are considered here: sea-level rise, temperature increase, increased winter precipitation, and changes in storminess. These factors influence coastal erosion, landslides, flooding and inundation, seawater intrusion, and invasion of exotic species.

Climate model projections of changes in sea-level pressure patterns (Figure 15) suggest a more southwesterly direction of winter winds, much like the strong El Niño events of 1982—83 and 1997—98. Combined with higher sea levels, these changes suggest an acceleration of coastal erosion.

The heavier winter rainfall that is projected by nearly all of the climate models suggests an increase in saturated soils and landslides. Flooding is more likely at the mouths of many of the rivers, especially those draining low-lying coastal basins which are already susceptible to flooding.

Projections of global sea level rise by the Intergovernmental Panel on Climate Change (IPCC) [72] in the next century are 2.0—8.6 mm/yr (7.9—34 inches per century), compared to 1—2.5 mm/yr observed during the last century. These rates imply sea levels on average 50 cm (20 inches) higher by 2100, but because of vertical land movements and shore slopes, any given location may experience very different changes in sea level and shoreline. On the Pacific coast, eustatic sea level rise is affected by a highly variable pattern of subsidence and uplift: uplift maxima centered at the mouth of the Strait

of Juan de Fuca (2.5 mm/year, or 10 inches per century) and the Columbia River (1.7 mm/year, 7 in/century) exceed eustatic sea level rise, resulting in a net relative sea level decrease [145].

In Puget Sound, land subsidence ranging from zero in the Strait of Juan de Fuca and north Puget Sound to 2 mm/year in south Puget Sound produces a local sea level rise that is greater than the global average. Furthermore, local changes in ocean circulation and heat content can also alter sea level: the Hadley Centre climate model projects higher increases over the next century for the Pacific coast of North America than for the Atlantic coast.

Sea-level changes are not the only factor with the potential to affect coastal areas. In low-lying areas, the frequency of storm surges may be more significant than sea-level rise alone [78].

As was mentioned in the previous section, very little work has been done on the connection between climate and coastal ecosystems. As a result, very little is known about how climate change could affect these ecosystems. However, it seems likely that these ecosystems would be unaffected by the combination of temperature increases, changes in the timing and volume of freshwater input to the coastal zone (see section 2.3), and possible changes in ocean circulation, stability, and thermal properties.

5.4 Socioeconomic impacts of the likely changes

Tourism and seasonal visitation dominate economic activity in the communities along Washington and Oregon's Pacific coast. The populations of the small coastal towns and cities swell during the late spring and summer as visitors are drawn by opportunities for beach-walking, horseback riding, recreational fishing, kite-flying, etc. As an example, the City of Ocean Shores, Washington, with a permanent year-round population of approximately 3,300 residents, attracts more than 1.5 million visitors each year. In addition, some coastal communities also rely on commercial fishing, shellfish aquaculture, and agricultural production to help drive their local economy.

Within the interior of Puget Sound, the coastal towns and cities are part of a much more diverse, interdependent economy. The Ports of Seattle, Tacoma, and Everett have developed into major international shipping destinations, importing and exporting raw commodities and finished products to and from the other Pacific Rim countries. However, local economic activity is no longer dependent on shipping, and the region has diversified into a variety of high-tech and service industries. In addition to the major urban developments at Olympia, Bremerton, Bellingham, Seattle, Tacoma, and Everett, much of the Puget Sound coast is lined with residential properties of varying size and density. Along the eastern shoreline many of these homes are permanent full-time residences, while along the western coast of the Sound vacation properties and seasonal residences are more common.

Because beachfront property is so highly prized, much of the most significant private development along the exterior Pacific coast has been built directly along the shoreline, or in low-lying areas immediately inland. In recent years, larger multi-family developments and hotels have been added to the existing stock of oceanfront single family homes. Depending on their exact location, these properties could be threatened by long-term erosion, storm damage, and/or flooding. Within the less diversified economies of the smaller communities, damage to this type of commercial and residential development could be devastating. For example, in the City of Ocean Shores, beachfront erosion now threatens an area that represents more than 10% of the City's property tax base. If climate change and erosion accelerate the erosion trends that have emerged recently along parts of the coast, this type of scenario could become more common.

Private interests in aquaculture and commercial fisheries could also be threatened by the physical changes associated with climate change. Oyster production and crabbing generate significant revenues for the communities along both Grays Harbor and Willapa Bay. Any threats to the tide flats and estuarine areas of the Coast could damage these industries. Furthermore, in other areas, flooding or saltwater intrusion may threaten lands that are productive for agricultural or grazing.

In addition to the significant private investments described above, important public assets could also be placed at risk. Currently, erosion already threatens important public resources along the Washington coast:

- For several miles along the northern shore of the entrance to Willapa Bay, State Route 105 sits perilously close to the shore.

Shoreline armoring and beach nourishment have been used to help stabilize the nearby shoreline, but erosion still threatens the road.

- At Ocean Shores, the City's recently renovated wastewater treatment facility sits in a low-lying area that is subject to flooding and erosion. The facility is surrounded by hardened protection and efforts may be taken soon to reinforce the existing defenses.

- Near the mouth of the Columbia River, erosion is threatening facilities at Washington's Fort Canby State Park.

These examples highlight the importance of developing management alternatives for the Pacific coast that consider the threats that climate change and sea level rise pose to both public and private assets.

As noted previously, along the interior coast of Puget Sound, much of the shoreline has already been armored to protect urban centers, residential development, and railroad rights-of-way. Given the level of investment represented in many of these more densely developed areas, threats from sea-level rise and flooding will likely be met by efforts to reinforce the existing shoreline protection. However, such protective measures could still prove costly. For example, a detailed analysis of conditions along the waterfront in the City of Olympia suggests that existing shoreline protection will not be sufficient to safeguard some areas from inundation, if the more aggressive projections of sea level rise prove to be accurate. Additional challenges will be posed by the potential for more frequent and widespread flooding as sea level rise compromises operation of the City's stormwater system.

5.5 Coping options for resource managers

State and local officials are, to varying degrees, slow to incorporate climate change response into their management of coastal resources, coastal hazards, or land use. This is likely due to the inherent uncertainties of climate change scenarios as well as the inertia seemingly built into institutional processes and arrangements. A series of interviews with coastal managers shed light on the way they use (or do not use) climate information [78].

5.5.1 Coastal Flooding

After examining the influence that climate variability and change have on the coastal management system with respect to coastal flooding, we can determine the level of adaptability of the management system to climate. In summary, we found:

- The management system places highest priority on riverine flooding.

- Legal barriers and constraints limit the management system's ability to incorporate climate issues.

- Floodplain mapping efforts are based on the existing environment (100-year floodplain).

- Management decisions are often based on probabilistic, statistical, and historical analysis of past events.

- Climate issues are overshadowed by existing and potential Endangered Species Act listings of various salmonid species.

Given these primary findings, it appears that the coastal management system is not very adaptable to the implications of climate variability and change even to existing threats of coastal flooding. When questioned about their respective levels of adaptability, the responses from the interview participants ranged from a general feeling of adaptability, based on an ability to adapt within a moderate timeframe, to the response of "not very adaptable, flexible, or rapidly capable of change." It appears that the level of adaptability is closely linked with the time horizon within which agency planning is based. Emergency response planning is therefore fairly sensitive, based on the fact that planning is a constant and ongoing process within Washington's Emergency Management Division. EMD does not view emergency management as an event that happens when a siren goes off, but instead as a process of constantly changing roles, responsibilities, and circumstances based on hazards that exist today and those that may exist tomorrow. On the other end of the scale, however, are agencies with 10—20 year planning horizons. These agencies have a much harder time viewing their management system as sensitive to climate and do not readily see how a seasonal forecast, let alone a 20—50 year climate change scenario, may be of use in decision-making.

It was especially striking that the majority of the participatory agencies did not view climate change impacts, specifically with respect to long range projections of coastal flooding, as a risk to the resources they manage. This lack of recognition is what undoubtedly is limiting consideration of climate related impacts in coastal flooding management in Washington State.

5.5.2 Coastal Erosion

The ongoing issues presented by the erosion on the southwest Washington coast are forcing the realization that Shoreline Management Act (SMA) erosion policies need to be reexamined cooperatively between agencies in light of the changes in the natural system. The City of Ocean Shores is currently in the process of making procedural changes to their Shoreline Master Program (SMP), and will begin considering significant land-use in the near future. The SMP was originally adopted in 1974, when the Southwest Washington coast was in an era of more-or-less dependable shoreline accretion, but the system has now shifted to an era of localized erosion, and the City has realized that it does not have adequate policies to address erosion. The timeliness of its planning process, and erosion associated with the 1997—98 El Niño event, should be creating the awareness needed to facilitate consideration of climate variability and change factors into the management system. The Washington State Department of Ecology, recognizing that the broad erosion policies of the SMA need to be updated, has included such measures in an updated implementing regulation.

5.5.3 Invasive species

Unlike many of the agencies that manage resources impacted by coastal flooding and coastal erosion, the Cordgrass management community is much more flexible and adaptable on timescales of a few months to a few years. County weed boards and other agencies with management responsibilities for Spartina control often adopt management plans on an annual basis. Control efforts, including the use of chemical and/or herbicides, are regularly planned on a day-to-day basis, as water quality protection guidelines limit application during high winds, high tides, and precipitation events.

The majority of the interview participants felt that they would be able to adapt their management and control efforts within a short time frame and could make use of El Niño forecasts. They were reluctant, however, to base irreversible management decisions solely on 30—90 day climate forecasts or forecasts of upcoming El Niño events. Their hesitation was based primarily on the fact that the hypothetical example given was for a forecast for a cooler-than-normal year [36]. Since such a year would reduce Cordgrass growth, the response to such a forecast would be to refrain from initiating new control activities that year. But managers were concerned that if they did so and the forecast turned out to be in error, they would be worse off. The failure to control seedlings and new growth, for even one year, would represent a “lost cause” in the eyes of the management community.

Overall, participants were very receptive to the prospect of gaining a better understanding of the link between climate and Cordgrass growth. They mentioned that funding from the State legislature was directed toward eradication and control, and not for additional research; they hoped that projects such as the one being conducted by the JISAO research team could help bridge this gap.

5.5.4 Summary of institutional issues

The agencies that were interviewed exhibited various degrees of actions to incorporate climate change factors into their decision-making process. Collectively, the agencies were aware of and were considering climate-related impacts through particular governmental processes, but were not necessarily identifying climate change as a causal component for the principle issues of concern. Consequently, they were generally not changing regulations or policies as a response. *Because of the inherent uncertainties of climate change and lack of convincing evidence about the impacts, there is little motivation to initiate or adapt policies that will address climate factors.*

The local planning department is able to respond directly, because of the more regional level of government which may allow greater flexibility in terms of making changes in administrative rules or regulations through adaptations of the comprehensive plans. Many of the other agencies are simply unable to change in this nature due to the limitations on their authority. Due to the extent of their regulatory jurisdiction, it is often beyond their capacity to manage the resources.

Because of the nature of the comprehensive planning process, the one important strategy that a planning department can undertake is to improve the manner in which geo-technical information is used in approving developments and to create better standards and stricter criteria for reports through local plans. Based on substantiated climatological forecasts, the geotechnical reports should take into account the landform and environmental conditions subjected to impacts from climate change and then make statements about setbacks, or safety and building codes given that vulnerability. Plans may also be developed to include site-based information including detailed descriptions of the types of building periods and flood zones that are appropriate. This way, assumptions that go into development of various sites would be drastically improved.

Subsidies and support for development should also be weighed according to the potential vulnerabilities of particular regions and sites. Moreover, climatological information should be properly disseminated not only to those who grant the support for development, but also to the public who are buying into it. A system of disincentives may therefore limit growth in hazardous areas and avoid the scenario where governments have to react after-the-fact.

As our society continues to expand into regions with significant coastal hazards, the need for sustained action taken to reduce or eliminate risks to people and their property should be a priority. In addition, the need to find means to limit disaster costs is evident. Effective forecasting as a method of cost-effective hazard mitigation may provide an answer. Identification of climate change as a causal component and consideration of climate factors within management strategies is a necessity for proper planning that will eliminate the risks to resources. A proactive, avoidance strategy based on a heightened adaptability to climate changes may circumvent the damages and save the entire management system from having to react to situations of great loss.

While significant investments now exist in the coastal areas threatened by climate change and sea level rise, the most serious challenges for managing economic risks may be in controlling the pressure for additional shorefront development. Although much of the coastline still remains undeveloped, the coastal communities along the Washington and Oregon coast have grown rapidly over the past twenty years. If the regional economy continues to thrive, the pressure for additional tourist development will only grow larger. Increased residential and commercial densities along the ocean should be expected if existing management policies remain unchanged.

To date, few coastal communities have considered the potential threat posed by climate change and its potential role in coastal planning. However, long-term economic impacts and the range of future response actions may be dictated by planning decisions made now. Efforts to control or manage development may be essential for controlling economic losses and minimizing future calls for expensive protection measures.

Obviously, placing less property at risk in low-lying areas or on or downhill of unstable slopes would be the primary means to reduce the impact of climate change. There appears to be little inclination to move in that direction, however. Coastal property values continue to increase dramatically as society places a premium on attractive views and recreational access to the water. The "collective disaster memory" is so short (say, two years) that people can rarely be persuaded permanently to abandon dangerous property, even when their neighbors have died in mudslides [9].

One way to reduce the broad economic impacts of coastal erosion would be to assign to the property owner more of the risk associated with building in the coastal zone. Purchasers or developers of coastal property could be required to have the property analyzed by a geologist to determine soil stability and risk from sea-level rise. Insurers could then set premiums in keeping with the risk, and the purchaser of a high-risk property would have to decide whether the gain is worth the risk.

Beyond the considerations of minimizing property loss as climate changes, it would be appropriate to begin thinking about protecting coastal ecosystems. Considerable work needs to be done before we understand how these ecosystems would be affected by climate change, and therefore how best to protect them or to maximize their adaptability. One issue, the loss of wetlands to sea level rise, has been addressed on the east coast by the concept of "rolling easements"[153].

6 Comparison of Impacts of PDO and Climate Change

In the previous five sections we have outlined some of the impacts of climate variability and change on the region's water resources, salmon, forests, and coasts. The impacts of PDO are generally the same size or larger than the impacts of ENSO. It would be useful to compare the impacts of PDO also to the impacts of climate change. This has been done in part in section 2.4 for the reliability of various objectives in the management of the Columbia River Basin.

Here, we compare the average value of several quantities during the warm and cool phases of PDO. The averages are calculated over the warm (1925—45, 1977—95) and cool (1900—24, 1946—76) phases of the PDO, after detrending the data. The results are expressed as a percentage of the average value (except for temperature). Most of the data have been presented in this report. We also compare these to the values for the 2050s from our climate modeling work. The results are shown in Figure 45. The fluctuations in annual average temperature associated with the PDO, from Figure 11, are quite small, especially compared to the changes projected by the climate models. The value shown is the average of the seven scenarios for the 2050s; see Table 3. The PDO-related fluctuations in annual precipitation are comparable to those for the climate models; note, however, that the models tend to produce wetter winters and drier summers.

The PDO snow depth fluctuations are averages from January 15 to April15 at Snoqualmie Pass, Washington, and are taken from the data used to produce Figure 21. Note how much bigger the variations are than the variations in precipitation, because of the tendency for PDO to produce winters that are either warm-dry or cool-wet. For the climate change value of snow depth, we use the decline (averaged over the same period) in snow water equivalent over the entire Columbia Basin as reported in the work of Hamlet and Lettenmaier [60] (their table 6). While this is clearly not the same as snow depth at Snoqualmie Pass, it gives a rough idea of the magnitude of snowpack changes. In fact, the average snow depth at Snoqualmie Pass is likely to decrease much more than is shown here, since in the model simulations the remaining snowpack becomes increasingly concentrated at high elevations (especially in Canada; see Figure 26). It is also worth noting that Hamlet and Lettenmaier found larger decreases in snow water equivalent later in the season. Therefore, comparing values at, say, April 15 would give more dramatic results than the average shown here.

The streamflow value is for the April-September average and is taken from naturalized data at the Dalles (Figures 22, 23) for the PDO portion of the figure and from the model simulations by Hamlet and Lettenmaier [60] (their table 7). As with snowpack, note that the PDO-related fluctuations are much larger than the fluctuations in precipitation. The PDO tends to have amplified response in the region's water resources. Under climate change scenarios, the average summer streamflow becomes like the drier decades in this century. Note, however, that the changes in the hydrograph are more dramatic during the summer months (Figure 27); the April-September average masks some very large changes in June through September.

The "salmon" data are records of Washington Coho catch from Hare *et al.* [61] but were not actually presented here, though the results are similar to those shown in Figure 36. The PDO clearly has a huge impact on the average salmon catch for this particular stock. (Other Washington stocks have a more muted response, but many Alaska stocks show an even bigger PDO-related fluctuation). The future changes in salmon are purely speculative because it is not possible to estimate quantitatively how salmon will fare in the future, but it is fairly clear that they face a hard road as the climate warms and summer streamflow drops.

For forest fires, the data are as presented in Figure 38 and reflect average area burned (as a fraction of area monitored) over Washington and Oregon. Future changes are pure speculation, but there are some indications that forest fires could increase dramatically in frequency and intensity.

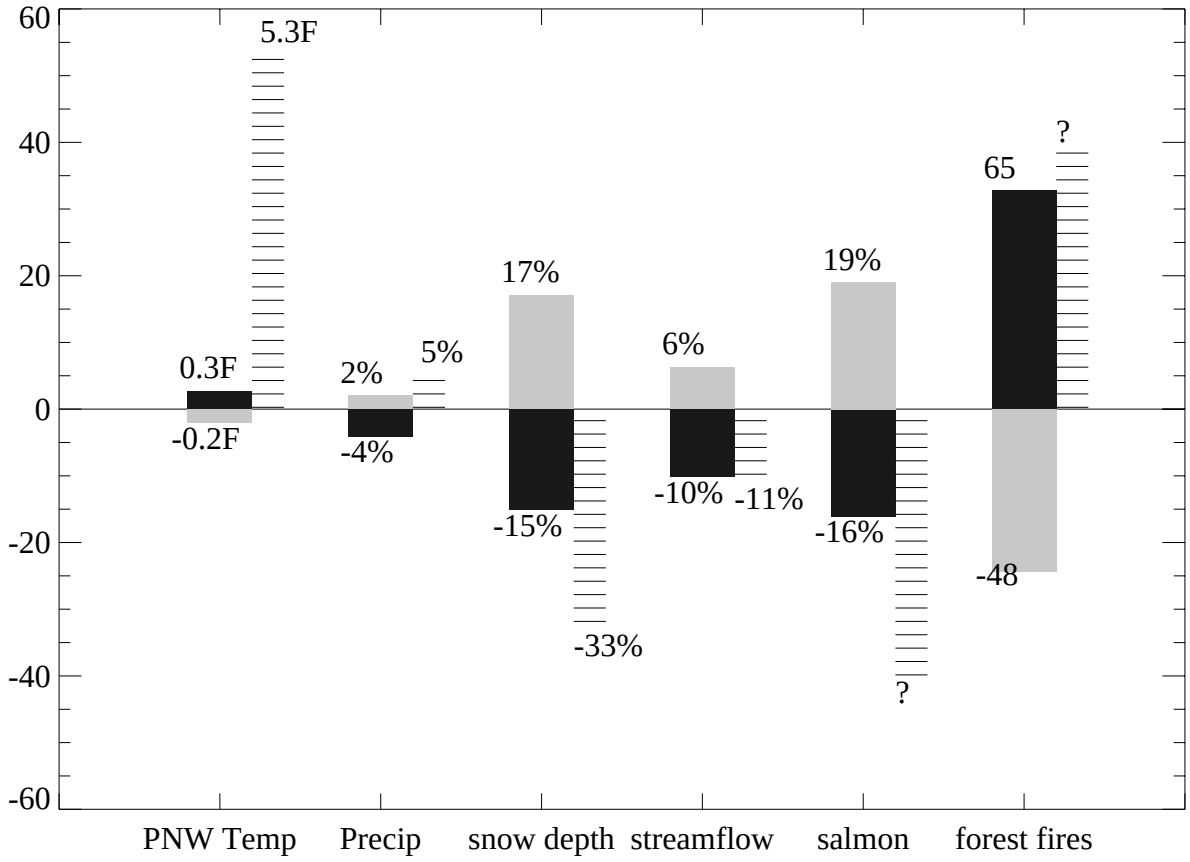

Figure 45. Changes in various quantities with the warm (black bars) and cool (gray bars) phases of the PDO, and under climate-change scenarios for 2050 (hatched bars). The abscissa is in percent except for temperature and forest fires. For details, see text.

7 Information Gaps and Research Needs

A pervasive theme of the forgoing discussion is that many important questions remain unanswered. Some of these are science questions and some are policy questions. The list that follows, which is an update of that in Snover *et al.* [146], is by no means exhaustive, but outlines some high-priority items that should be pursued in order to complete the picture of how climate impacts the Northwest and how the region can best prepare for future climates.

7.1 Numerical modeling

Numerical modeling of the climate system can address many pressing problems relevant to the Pacific Northwest. A regional integrated assessment relies on a range of climate models to generate broad-brush scenarios of climate change, but these scenarios must be applied at finer scale. The poor topography currently used in most climate models is a limitation to the quality of climate-change scenarios that these models produce. Regional climate models, especially when coupled to numerical models of the region's rivers, estuaries, and coasts, may be able to address many types of questions. Some of these include how climate change could affect smaller-scale processes like coastal upwelling, the interaction of freshwater and saltwater in the estuaries, the nature of windstorms, and the frequency of rain-on-snow events.

Climate modeling with a high-resolution regional model (see section 1.2.4) can improve the topography and many aspects of model climate, but the biases can be as big as in a global model, in large part because regional models still rely on global models to provide fluxes of heat, moisture, and momentum at the outer boundary of the regional model. An alternative approach is to use a model with a stretched grid [31], in effect giving a global model high resolution over one area; this approach is only practical for a major modeling center, but may be a useful supplement to existing modeling tools at such centers.

In our analysis of climate model scenarios, we have mostly used decadal averages. But these averages can mask important aspects of how climate scenarios play out in time; see Figure 19. To give a more specific example, in the Hadley scenario, the decade of the 2020s happens to be unusually wet compared to other decades; this strongly affects the conclusions concerning snowpack and water resources. It would be instructive to analyze the interannual and interdecadal variability in these model scenarios. Changes in the frequency, amplitude, and other characteristics of ENSO and PDO could have as dramatic an effect on the Northwest as the gradual changes in temperature.

7.2 Climate analysis and prediction

A crucial question for near-term (next few years) management of natural resources is whether the PDO has changed phase to the cool phase, or indeed whether the notion of phase changes is truly applicable to the PDO. Considerable work needs to be done by climate dynamicists to answer these questions. Gains in understanding of the behavior of North Pacific climate would have enormous potential value.

It would also be very valuable to explore in more detail the connections between *summer* climate and PDO and ENSO, with a view to improving predictability of summer climate in the PNW. Most work on seasonal variability and prediction, and most of our analyses, have focused on the winter season, because this is the season when the connections are strongest and predictability is highest. But for water resource managers, many of the most troublesome aspects of their responsibilities are balancing supply and demand during the summer, when they must watch water dwindle in reservoirs without knowing when autumn rains will begin to replenish the reservoirs. Advance knowledge of the severity of the summer or the timing of the onset of fall rains would be valuable. Analysis of past climate patterns (like those connected with PDO and ENSO) may provide clues that would enable us to make such predictions.

Another line of research that ought to be undertaken concerns what is called the *attribution* of climate change. As Figures 13 and 14 show, there are significant trends in temperature and precipitation in the Northwest. But are these caused by increasing concentrations of greenhouse gases? We have made a first attempt to attribute them to natural climate variations, finding that a small but significant fraction of the trend can be explained by the PDO (see page 16). However, it would be useful to know whether this warming is indeed the local signal of global warming. Future policy decisions at the regional level may be more palatable if scientists

can say with some level of confidence that the observed warming can be attributed to human activity. At present, attribution has only been successful at spatial scales larger than that of the Pacific Northwest.

Because many of the most important impacts of climate depend not on the means but on the extremes, a line of research we are beginning to follow focuses on the climatology of extreme events. Lowland snowstorms, wind storms, damaging ocean waves and crop-damaging frosts are examples of extreme events.

Many important aspects of the environment are not well-monitored, like the soil moisture. Seasonal forecasts of climate and streamflow would be more successful if a monitoring system were put in place.

A final aspect of regional climate that could be better understood is its long-term history. We have reported above (in section 1.1.5) on a few attempts to reconstruct the climate of the PNW before the instrumental record began, but much more work needs to be done to understand the full range of natural climate variability and, to the extent possible in such data, the impacts that past climate variations have had. This may also help get at the problem of attribution mentioned above.

7.3 Impacts of Climate on Natural Resources

While the Climate Impacts Group has quantified some of the connections between climate variations and certain aspects of natural resources, much work remains to be done. In particular, the direct and indirect impacts of climate on Northwest forests needs to be analyzed further, and we have made great strides in collecting the data needed to do this. Very little work has been done in quantifying the impacts of climate variability on the region's coasts.

Apart from the analysis of how climate change and population growth will affect demand for water in Portland (section 2.4.3), we have not considered quantitatively how population growth will affect the natural resources that are also affected by climate change. The implications of shifts in consumption patterns, transportation requirements, land-use planning, and so forth, need to be explored in the context of a changing climate.

As a general issue for any quantitative analysis of changes in natural resources, it would be extremely valuable to compare the impacts of climate change to those of observed variability in more depth than was done in the previous section. The methods of Hulme *et al.* [71] offer an elegant way to do this, and could be applied to our quantitative regional modeling work (mainly in hydrology) and also to the forest modeling performed in connection with the National Assessment.

Perhaps the most critical research need in this area, however, concerns the role of climate variability and change on the open-ocean phase of the lifecycle of salmon. The archival-tag data discussed in section 3.3 offer a promising new source of information about the behavior of salmon in the open ocean, which is already leading to new insights. Nonetheless, we are a long way from understanding how climate affects salmon and ecosystems in the ocean, and salmon recovery plans (currently being discussed) would benefit tremendously from an improved understanding in this area.

7.4 Policy Implications

In sections 2.5, 3.5, 4.5, and 5.5, we suggested a wide range of possible coping options, but none of these have been analyzed in any detail. Extensive socioeconomic, institutional, and policy analysis needs to be done to determine which are the most feasible, economically and politically, and to determine the best approach to implementing them.

A prime example is the idea of water markets in the Columbia Basin. We pointed out that in the present system of water allocation, shortages in summer water supply fall disproportionately on some users while other users receive their full amount. Introducing a system of water markets would encourage conservation and would promote water going to its highest-value uses. However, it would overturn decades of practice and would place a heavy burden on certain users of water. Considerable analysis needs to be done to determine the full impacts of such a shift, and to determine the best way to compensate those who would lose in such a shift.

In order to understand these issues fully, more work needs to be done in understanding institutional design and adaptation in the face of anticipated changes in climate. Existing rules and governance structures are

likely to persist well into the future and will be of overriding importance as the region reacts to climate extremes and climate change. The status quo is, as our analysis showed, often inadequate if not counterproductive in dealing with extremes and change. The focus must therefore be on developing the institutional infrastructure and capacities to implement the kinds of policies that may be enacted in response to climate change. Since so many aspects are water-dependent, we need to pay particular attention to systems and assumptions underlying water allocation procedures.

For water resources and salmon, and to a lesser extent forests and coasts, binational issues with Canada are of considerable importance and need to be examined. For example, the hydrological modeling work (see Figure 26) suggests that as the region warms, a greater proportion of the Columbia Basin's snowpack will lie in Canada. What are the policy implications of such a shift, especially if Canada were to seek to address its own climate-change related problems by changing the patterns of water storage? Another example concerns salmon. Already, binational conflicts over certain salmon runs have led to heated confrontations both on land and at sea. The U.S. and Canada recently signed an agreement concerning salmon, the Pacific Salmon Treaty, after many years of difficult negotiations. Some of these issues have been addressed by Cohen *et al.* [23], but more work remains to be done.

Another aspect of policy work that should be addressed is the interactions between sectors. Again, Cohen *et al.* [23] has examined in some detail the inter-sectoral conflicts and opportunities in the Columbia River Basin. A prime example not discussed there concerns the question currently under debate about whether to remove four dams from the lower Snake River in order to improve the viability of salmon there. Our "coping options" for giving salmon the best chance at surviving climate change focus on restoring salmon habitat, which imply removing some dams. But in our coping options for water resources, we suggest increasing storage, which implies preserving dams and perhaps even building more dams (though there are few remaining usable sites for new dams). Because we were simply listing some policy options, we have not sought to resolve such apparent conflicts in our coping options, but clearly this should be a priority before reaching a decision about removing the dams.

Finally, throughout our lists of coping options in the abovementioned sections, a theme was the need for a **regional climate service**, which would provide relevant and timely information concerning climate fluctuations and trends on a variety of timescales. Such a service would also maintain an active dialog with users of the information in an ongoing assessment of the impacts of climate variability and change in the Pacific Northwest.

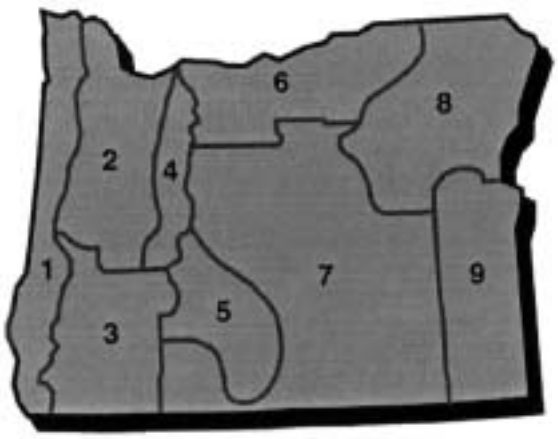

Figure 46. Climate divisions for the state of Oregon. Source: National Climate Data Center

Part III

Appendices

A Climate Data

We use two primary sources of climate data: climate division (CD) data and historical climate network (HCN) data. HCN data are individual stations with long records; climate division data are aggregates of available data within a given geographic area and are meant to represent average values over that area (see Figure 46 for the climate divisions in Oregon). We use HCN data for trend analysis and CD data for studying interannual variability and for forming spatial averages.

The HCN data set[1] [82] provide the best data for analysis of trends over the twentieth century, especially when averaged across climate divisions (see below). For monthly mean temperatures, the adjusted data are preferred, but for precipitation, unadjusted climate division data are preferred and have been used with success. These data will be available on the NCDC home page. Trends of daily temperature and precipitation can be evaluated by using a subset of the US HCN monthly data, which is based on 1221 stations across the conterminous U.S. and 46 stations in Alaska. In the PNW there are 113 stations, and 90% of the records go back at least to 1915. In the HCN data set used here, inhomogeneities in the data record (e.g., due to station relocations or instrument changes) have been removed, and the component of trends attributable to urbanization has also been removed [81]. For trend analysis we first average the station data by climate division, then form a regional average by area-weighting the climate-division results, and finally calculate the linear trend.

The climate division data are made up of all reporting measurements within a geographic area, aggregated by month. Climate divisions are used to group observations in climatically similar sections of each state, as shown for illustrative purposes in Figure 46 for Oregon. There are 10 climate divisions in Washington, 10 in Idaho, and 9 in Oregon, for a regional total of 29. To form a regional average, we area-weight the climate division data. See http://www.cdc.noaa.gov/USclimate/USclimdivs.html for information and maps; see http://www.wrcc.dri.edu/spi/divplot1map.html to examine time series for a specific climate division.

For both datasets, the stations are disproportionately located at lower elevations. For example, the highest HCN station is at Crater Lake, Oregon, with an elevation of 6475 feet (1962m), and only 7 stations are located above 5000 feet (1515m); a substantial fraction of the state of Idaho, and parts of Oregon and Washington, lie above this elevation. This elevational bias in station location probably introduces a warm bias to the area-average temperature and a dry bias to the area-average precipitation (K. Redmond, pers. communication, 1999). These biases are unlikely to affect our results substantially. Mapping programs that take into account elevation and slope, like the one used to produce Figure 2, offer a more realistic view of the spatial variations in precipitation especially.

[1]For more details, see http://www.ncdc.noaa.gov/ol/climate/research/ushcn/ushcn.html.

B Methods

B.1 Climate analysis

Empirical orthogonal functions

Empirical orthogonal function, or EOF analysis, is commonly used in the atmospheric sciences to identify coherent patterns of variation in data. It produces spatial patterns (EOFs) that are ranked according to the fraction of total variance they explain. Associated with each EOF is a principal component time series (PC), whose mean value is zero, that describes how well the EOF pattern is correlated with the observed pattern at a given time. (As an illustration of the difference between EOFs and PCs, see the spatial patterns and time series, respectively, in Figure 6.) For example, suppose we have a simple dataset of temperature at five stations, $T(n,t)$, where T is temperature, n represents the station, and t denotes the time of observation. EOF analysis would generate patterns showing coherent variations in temperature among the five stations; for example, if the stations were in the same region, the first EOF would probably highlight the tendency for all stations to be warm or cool at the same time. The PC (which represents the time component) in that case would show when all the stations were warmer or cooler than normal. The second EOF might highlight the subtler tendency for two stations to vary together and in opposition to the other three. This EOF would also have its own PC, showing the times when this tendency was exhibited in the data.

EOF analysis can also be performed on datasets consisting of different types of variables, provided the variables are first normalized (divided by their standard deviation). EOFs can identify the dominant patterns of correlation across different variables. For example, EOF analysis of the five stations mentioned in the previous paragraph could also include precipitation. If temperature tended to be negatively correlated with precipitation, EOF analysis would reveal a tendency for warm days to be dry and cool days to be wet at all stations.

The results of the EOF analysis performed here are discussed in section 1.1.1.

Processing of climate model output

Because of the coarse resolution of the climate models, we do not believe that any reliable information can be gained from the spatial variations within a region the size of the PNW. Model output is therefore spatially aggregated before plotting. Because this was done largely in support of the hydrological modeling, the region over which it was performed was in fact the Columbia River Basin (CRB), not the three-state region which we define as the PNW. We do not expect the differences between the model output over the CRB and the PNW to be meaningfully different.

For both temperature and precipitation, 10-year averages for the 2020s, 2050s, and 2090s from model output for each calendar month are compared to output from a control (constant, pre-industrial CO_2) simulation. For temperature, the comparison is a difference, while for precipitation, the comparison is a ratio. Spatially-aggregated changes are formed by simply averaging the model changes over the CRB. To convert the precipitation ratios into inches as shown in Figure 14, the area-averaged model ratio is applied to the area-averaged monthly climatological value from observations (Figure 3).

B.2 Interviews of resource managers

A series of interviews were conducted by Bridget Callahan, David Fluharty, and Edward Miles. For brevity we discuss here only the interviews of water resources managers [19]; the methods, questions, and variety of interviewees were similar for other sectors.

For the water resources sector, the interviewers conducted 31 interviews of forecasters and water managers at 28 different organizations in the Pacific Northwest. Interviewees included individuals and groups of planners, hydrologists, engineers, climatologists, regulators, and analysts in private, municipal, state, federal, and tribal organizations. Each interview began with a description of the Climate Impacts Group and its goals.

The interview questions were fairly extensive, and are summarized here by theme. Some are applicable only to certain interviewees (e.g., number 5 only for those who make some kind of forecast themselves).

1. What are the major tasks and responsibilities of your organization? From what legislation does its authority derive?

2. What is the size of your organization and of its scientific staff? Does it have the technical capacity either to produce or use climate (>30 day) forecasts? Does your organization need climate information?

3. What are the most important jobs you perform in managing water resources?

4. What have been the most important issues you have faced recently? Have they been characterized by conflict or consensus?

5. If you make forecasts, describe the technique you use and the interactions with the users of forecasts.

6. How important are the seasonal forecasts issued by the National Centers for Environmental Prediction? How do you respond to them for providing water supply and/or water quality?

7. In what form do you receive seasonal forecasts and how are they used in making decisions? What factors limit your use of forecasts?

8. How sensitive and how vulnerable to climate are the resources that you manage?

C Models used for regional analysis

C.1 Climate models

Several climate model runs have been used here. The "first" generation (1995 models) are from the Max-Planck Institüt für Meteorologie (MPI) [137], UK Hadley Centre (HC) [75], and Geophysical Fluid Dynamics Laboratory [100]. The 1998 model runs came from the Canadian Climate Centre Model (CCC) [12], HC [75], MPI [137], and GFDL [100]. Many of the 1998 models were run at least twice with the same forcing but different initial conditions; we use only the first ensemble member each time.

The CCC and HC model runs used here have been validated against observations for the US [32]. The CCC is too cool by several degrees Celsius over much of the West in winter and spring, and is too warm over the PNW in summer. The HC model generally has a cool bias over the west in all seasons; in winter, the PNW lies between an area of cool bias to the south and an area of warm bias to the north. Precipitation is substantially overestimated in both models all year east of the Cascades, more so in CCC than HC.

CCC

The CCC CGCM1 transient scenario is derived from a coupled atmosphere-ocean general circulation model with transient greenhouse and sulfate aerosol forcing (1%/yr increase in equivalent CO_2 with sulfate aerosols from the IPCC emissions scenario IS92a). The CGCM1 time period is 1850—2100. The horizontal resolution was T31 truncation in spectral space (approximately 3.75˚ x $3.75˚) and the model had 10 vertical levels.

HC

The UKMO Hadley Centre HADCM2 transient scenario is derived from a coupled atmosphere-ocean general circulation model with transient greenhouse and sulfate aerosol forcing (1%/yr increase in equivalent CO_2 with IS92a sulfate aerosols). The HADCM2 time period is 1860—2099. HADCM2 is a grid-point model with a horizontal resolution of 2.5˚ latitude x 3.75˚ longitude, and the model had 19 vertical levels.

MPI

The MPI/DKRZ ECHAM4/OPYC3 transient scenario is derived from a coupled atmosphere-ocean general circulation model with transient greenhouse and sulfate aerosol forcing (IS92a equivalent CO_2 and sulfate aerosols). The horizontal resolution was T42 (approximately 2.8˚ x 2.8˚) and the model had 19 levels in the vertical. Unfortunately, a data storage problem meant that the results for the 2050s were not available, so we have used the 2040s instead.

GFDL

The GFDL transient scenario is derived from a coupled atmosphere-ocean general circulation model with transient greenhouse and sulfate aerosol forcing (1%/yr increase in equivalent CO_2 with IS92a sulfate aerosols). The horizontal resolution was R30 truncation in spectral space (3.75˚ x $2.25˚) and the model had 14 levels in the vertical.

Comparison of the climate models' configuration

The HC and MPI models have somewhat higher horizontal and vertical resolution than the other two, and also use a more elaborate land surface scheme. All four of the models are coupled to an ocean model and use flux adjustment, a common technique for preventing climate drift in coupled models. The CCC model uses a sea ice model with thermodynamic equations only, whereas the other three use dynamic and thermodynamic equations. The HC and MPI models have a sensitivity (global average temperature change for equilibrium experiments with doubled CO_2) of 2.6˚C, while the CCC and GFDL models have higher sensitivity, 3.5˚C and 3.4˚C respectively.

C.2 Models used for evaluating the effects of climate on the Columbia Basin

The modeling package shown in Figure 47 was constructed to evaluate a broad range of effects on Columbia Basin hydrology and water resources associated with climate variability and climate change.

Each of these models can be run individually using observed data, or may be linked together to provide a fully

integrated simulation of the climate/hydrology/water resources system. The mesoscale climate model used in this package was developed and implemented by researchers at Pacific Northwest National Labs based on the MM5 weather model. A primary feature of this model is a sub-grid parameterization for the distribution of precipitation that captures more of the spatial variability of precipitation associated with the complex PNW topography [92, 93, 94]. The model can be implemented at various spatial resolutions, and is typically run at about 60-90 km resolution, although higher resolutions are possible. The Variable Infiltration Capacity (VIC) macro-scale hydrology model was developed at the University of Washington 97. The model has been used to construct daily timestep simulation tools for a number of river basins in the United States, Europe, and S.E. Asia, and has been implemented at 1-degree resolution for the Columbia Basin [116]. This 1-degree implementation of the model has been used for all of the experiments described here.

The ColSim model is a monthly-timestep reservoir model that incorporates the major projects and operational features of the Columbia basin, and was constructed as a research tool for the experiments described here. The domain of the model is from Mica Dam in British Columbia, near the headwaters of the Columbia, to Bonneville Dam near the mouth of the river. It includes many of the major tributaries: the Kootenai, Pend Oreille, Clark Fork, and Snake River systems. The dams on the Yakima and Spokane rivers, however, are not simulated.

The input of the model is streamflow, month-by-month, for a given year, whether from observations (in which case the unregulated or "virgin" flow is used) or from the hydrology model driven by output from a climate model. ColSim can thus be used to explore reliability under hypothetical conditions like the climate of the 2050's.

The outputs of the model are the reliability of the following flow targets: flood control, hydropower production (both firm and non-firm), agricultural diversions from the middle Snake River, navigation, recreation, and instream flows for fish. More details can be found in Miles *et al.* [105].

C.3 PWB econometric model

The Portland Water Bureau econometric model represents demand for water over the entire service area. The model can be represented by the multiplicative equation

$$D = \alpha e^{\beta S} W^{\gamma} E^{\delta} e^{\theta Ind} e^{u}$$

where D is demand, S represents the seasonal variation in demand, W is a weather variable, E is an economic variable. The variable Θ_{Ind} consists of two indicator terms representing non-smooth changes: one represents the sharp increase in conservation after 1992, and the other represents the pronounced weekly cycle of demand (lower on weekends). Past data are used to determine the model variables.

The seasonal variables in the model are a set of continuous indicator variables (Fourier series) which account for seasonal changes in demand. The weather variables are maximum daily temperature and total daily precipitation, with various lags. They are present in the form of deviation from the respective historical averages for the period 1940—1998. This approach to generating weather variables allows the separation of seasonal influences from changes in demand attributed to day-to-day weather conditions. As a result, the seasonal changes in demand are explained by the seasonal variables alone.

To apply the two-stage forecasting procedure described on page 43 to the climate-change scenario, we first adjust the average temperature and second apply a specific weather year. We must take this approach because the model does not have a mechanism for directly adding changes in annual average temperature and precipitation. We focus on the peak season for demand (June—September) and construct three scenarios for input to the demand model, bracketing the seven climate scenarios outlined in section 1.2.1. The first scenario is a "best-case" scenario composed of (1) the largest increase in summer precipitation combined with the smallest increase in summer temperature (HC model), and (2) a weather year (1948) whose June—September and January—May precipitation anomalies are closest to those of the HC simulation. The "worst-case" scenario has the largest decrease in summer precipitation (early MPI simulation) and largest increase in summer temperature (early GFDL simulation), combined with a year (1991) whose June—September and January—May precipitation anomalies are closest to those of the MPI simulation. Finally, the

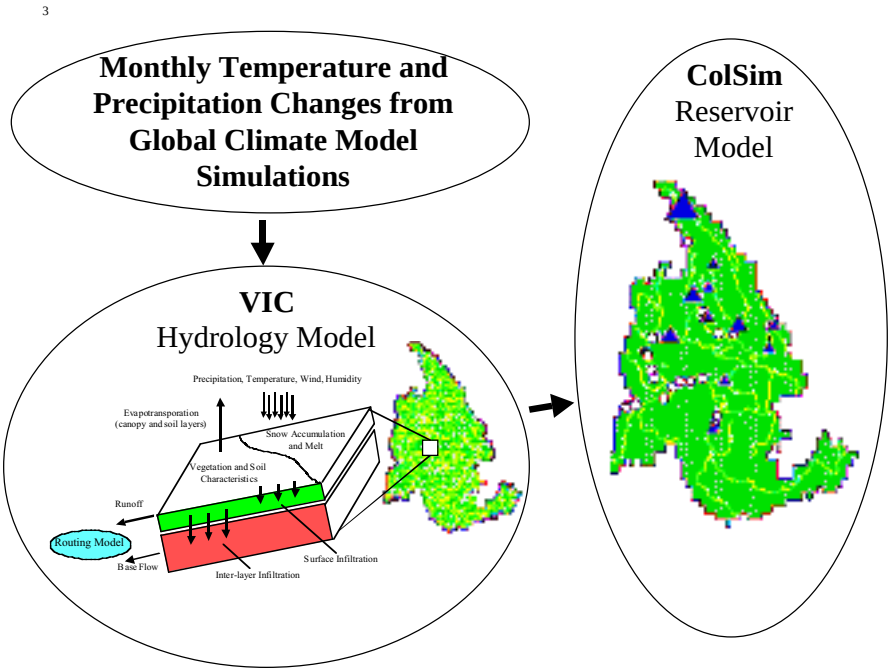

Figure 47. Hydrological modeling system used in this study.

"average" scenario has the average temperature change of all the models and a year (1980) whose precipitation was close to normal.

With representative weather years selected as described, we add temperature adjustments to bring each of the years up to the lowest, average, and highest average temperature changes from the seven model scenarios. The temperature adjustments for the three scenarios were 3.67˚F, 4.83˚F, and 6.72˚F. To use these adjustments in the yearly peak-season weather data from the econometric model, the following process was followed:

- The average maximum daily temperature over the peak season was computed for each of the three years selected;
- The seasonal averages were increased for each year by the amounts just mentioned
- The adjusted averages were proportionately distributed to the proper days in the peak season.

In using this approach, we assume implicitly that the daily temperature variations within the peak season are not affected by long-term climate changes. Rather, this approach adjusts all temperatures during the peak season in accordance with the projected overall rise in summertime temperatures. These adjusted temperature figures were used to generate the weather variables used for the demand forecast revisions.

D Population projections

As part of the National Assessment, NPA Data Services, Inc. has produced three alternate scenario projections for population and economic activity for the period 1997—2050. These projections are described in more detail in two documents issued by NPA [149, 150], which documents are summarized briefly here. We use here only the population projections.

The projections are available at several levels of spatial aggregation, from the level of counties and metropolitan statistical areas up to the whole USA. We have used the county data to form aggregates as indicated in Figure 4.

The three projections differ only in the choice of national-level assumptions and are intended to span the range of plausible outcomes. The high-growth scenario assumes robust growth in productivity and output fueled in part by vigorous immigration. The low-growth scenario projects stagnating population and economic growth and sharply curtailed immigration. The following key variables and assumptions are used in generating the population growth scenarios:

1. Birth rate. Based on high and low projections by the Bureau of Census in 1996.

2. Death rate. Also from Bureau of Census; rates for all three scenarios are the same after 2025.

3. Immigration. The high projection assumes that immigration will continue to increase at the rate that it did from 1987 to 1997; the low projection assumes a constant immigration of 300,000 per year.

From 1997 to 2050, the population of the USA grows from 267 million to 510 million for the high-growth scenario, 409 million for the baseline scenario, and 316 million for the low-growth scenario.

The interested reader may contact NPA for more information:

NPA Data Services, Inc.
1424 16th Street NW, Suite 700
Washington, DC 20036

E National Assessment

The Global Change Research Act of 1990 [Public Law 101-606] gave voice to early scientific findings that human activities were starting to change the global climate:

1. Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations

2. Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being.

To address these new findings, Congress established the U.S. Global Change Research Program (USGCRP) and instructed the Federal research agencies to cooperate in developing and coordinating "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural process of global change." Further, the Congress mandated that the USGCRP "shall prepare and submit to the President and the Congress an assessment which

1. integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;

2. analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health andwelfare, human social systems, and biological diversity; and

3. analyzes current trends in global change, both human-inducted and natural, and projects major trends for the subsequent 25 to 100 years."

The USGCRP's National Assessment of the Potential Consequences of Climate Variability and Change, which is focused most intensely on answering the question about why we should care about and how we might effectively prepare for climate variability and change, is being conducted under the provisions of this Act.

The overall goal of the National Assessment is to analyze and evaluate what is known about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. The National Assessment process has been broadly inclusive, drawing on inputs from academia, government, the public and private sectors, and interested citizens. Starting with broad public concerns about the environment, the Assessment is exploring the degree to which existing and future variations and changes in climate might affect issues that people care about. A short list of questions has guided the process as the Assessment has focused on regional concerns around the US and national concerns for particular sectors:

- What are the current environmental stresses and issues that form the backdrop for potential additional impacts of climate change?

- How might climate variability and change exacerbate or ameliorate existing problems? What new problems and issues might arise?

- What are the priority research and information needs that can better prepare the public and policy makers for reaching informed decisions related to climate variability and change? What research is most important to complete over the short term? Over the long term?

- What coping options exist that can build resilience to current environmental stresses, and also possibly lessen the impacts of climate change?

The National Assessment has three major components:

1. Regional analyses: Workshops and assessments are characterizing the potential consequences of climate variability and change in selected regions spanning the US. The reports from these activities address the interests of those in the particular regions by focusing on the regional patterns and texture of changes where people live. Most workshop reports

are already available (see http://www.nacc.usgcrp.gov) and assessment reports will start to become available in late 1999.

2. Sectoral analyses: Workshops and assessments are being carried out to characterize the potential consequences of climate variability and change for major sectors that cut across environmental, economic, and societal interests. The sectoral studies analyze how the consequences in each region affect the Nation, making these reports national in scope and of interest to everyone. The sectors being focused on in this first phase of the ongoing National Assessment include Agriculture, Forests, Human Health, Water, and Coastal Areas and Marine Resources, and Native Peoples/Native Homelands. Assessment reports will start to become available in late 1999.

3. National overview: The National Assessment Synthesis Team has responsibility for summarizing and integrating the findings of the regional and sectoral studies and then drawing conclusions about the importance of climate change and variability for the United States. Their report is to be available by spring 2000.

Each of the regional, sectoral, and synthesis activities is being led by a team comprised of experts from both the public and private sectors, from universities and government, and from the spectrum of stakeholder communities. These teams are supported in a shared manner by the set of USGCRP agencies, including the departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration), Energy, Health and Human Services, and Interior plus the Environmental Protection Agency, National Aeronautics and Space Administration, and the National Science Foundation. Through this involvement, the USGCRP is hopeful that broad understanding of the issue and its importance for the Nation will be gained and that the full range of perspectives about how best to respond will be aired. Extensive information about the assessment, participants on the various assessment teams and groups, and links to the activities of the various regions and sectors are available over the Web at http://www.nacc.usgcrp.gov or by inquiry to the Global Change Research Information Office, PO Box 1000, 61 Route 9W, Palisades, New York 10964.

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Academia is not the sole repository of knowledge or of inquiry, and we are grateful to have had long and fruitful interactions with people form many walks of life. These "stakeholders" have added a tremendously valuable perspective on many issues. These interactions have been both formal, at workshops like the one described on page 6, and informal, through e-mail and telephone conversations.

The National Assessment Coordination Office (NACO) made a number of important contributions to this report. Dr. Michael MacCracken, the director of NACO, wrote Appendix E. Ben Felzer gave invaluable assistance on the climate model scenarios. Lynne Carter provided assistance and encouragement at many steps along the way.

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