

IMPACTS OF GLOBAL CLIMATE CHANGE
ON THE
PACIFIC NORTHWEST

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INTRODUCTION & SCENARIO

Increasing atmospheric concentrations of greenhouse gases, including carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), appear to have changed the earth's climatic system, warming the earth's surface and producing other changes in climate. Global average surface air temperature has warmed 0.3-0.6°C (0.5-1.1°F)* since the late nineteenth century, a warming that appears to be caused at least in part by human activities. Continued emissions of greenhouse gases due to human activities are expected to cause continued warming, at a rate more rapid than any experienced in the last 10,000 years. By 2100, the earth's average surface temperature is projected to be 1-3.5°C (1.8-6.3°F) warmer than it was in 1990. This warming will not be uniform; some parts of the world will warm more than others. Increasing levels of greenhouse gases are also expected to cause an enhancement of the global mean hydrological cycle, and an accelerated rate of sea level rise.²⁸

While the various general circulation (computer) models (GCMs) that are used to predict future climate tend to agree on the global aspects of how climate will change, they are not yet sophisticated enough to produce dependable, consistent projections of climate change for smaller regions, such as the Pacific Northwest (defined for the purposes of this paper as the states of Washington, Oregon and Idaho). The coarse resolution of GCMs is insufficient to resolve local geographic features -- such as the Cascade Mountain range -- that are extremely important for regional climate. Regional-scale predictions of future climate are also hampered by the large amount of natural variability inherent to our climate. The climate modeling research community is actively improving model inputs and design in order to improve regional-scale climate predictions but is still hampered by GCM resolution, imperfect representation of atmospheric physics and lack of detailed local observations for model validation.

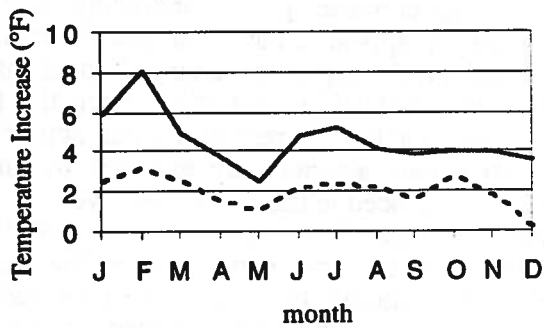
Throughout this paper, we will use a specific scenario of future temperature and precipitation changes in the Pacific Northwest to frame our discussion of the impacts of future climate change on the region. However, we will place much of the emphasis on vulnerabilities. The climate scenario that we use is taken from a GCM simulation of future climate, performed by a major GCM modeling center (the Max Planck Institute für Meteorologie, Hamburg),** interpolated to the regional scale. While MPI's global climate predictions agree in general with climate predictions made by other GCMs, agreement does not imply correct simulation of future climate. In addition, predictions made by different GCMs usually differ more substantially at the regional level; a different GCM would not predict the same scenario of climate change for the Pacific Northwest. The scenario chosen as a basis for discussion is *plausible* in light of our current understanding and computing capabilities, but should not be considered to be a *prediction*.

Under the MPI climate scenario, the Pacific Northwest would experience warmer, wetter winters and warmer, drier summers (see Figure 1). Annual average Pacific Northwest temperatures would increase 1.1°C (2°F) by the decade 2020 and 2.5°C (4.5°F) by the decade 2050. The warming would be fairly uniform over the course of the year, with slightly more warming during the winter (Fig. 1A). Because of the thermal inertia of the climate system, temperature is expected to continue to increase beyond 2050, even if atmospheric concentrations of greenhouse gases were stabilized by that time. Under the MPI scenario, precipitation would increase somewhat during the wintertime and decrease during summers (Fig. 1B), although projected precipitation changes are less certain than changes in temperature.

* To convert a temperature change in °C to °F, multiply by 1.8.

** The model simulation was a time-evolving, transient climate simulation using a coupled ocean-atmosphere GCM (MPI model ECHAM1-A; Cubasch *et al.*, 1992). The model was forced with increasing emissions of greenhouse gases using emission scenario IPCC IS90a (=1%/year as CO₂). This model run is one of several archived by the Intergovernmental Panel on Climate Change (IPCC) at the National Center for Atmospheric Research in Boulder, CO for use in integrated assessments.

1A. Monthly average temperature increase.



1B. Monthly average precipitation change.

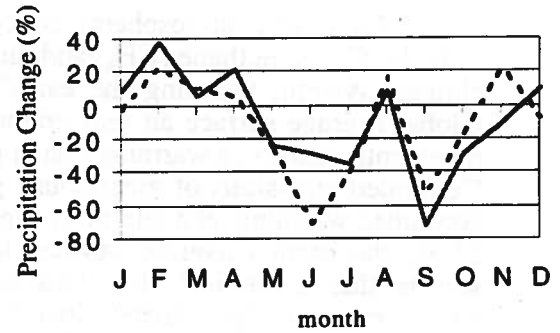


Figure 1. Average changes projected for the Pacific Northwest (Washington, Oregon and Idaho) in 2020 (dashed lines) and 2050 (solid lines) under the MPI climate scenario. (A) monthly average temperature increase; °F. (B) Monthly average precipitation change; % of current precipitation. Precipitation changes are a spatial average of fractional change in precipitation.

The model scenario indicates only how regional *average* temperature and precipitation might change; it doesn't address how climate variability would be affected by climate change. GCMs predict that climate change will lead to a decrease in the daily range of temperature in most regions. Overall, warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days. Climate change may also result in an increase in precipitation intensity, or extreme rainfall events. These predictions are less certain than projections of average changes in temperature and precipitation and may or may not specifically apply to the Pacific Northwest. It is currently impossible to predict whether there will be future changes in storminess. Although GCMs currently project gradual climate change, there is a possibility that the climate system may respond in surprising and/or sudden and unforeseen ways.^{28,8}

Much of the variability in Pacific Northwest climate results from variations in the wintertime position and intensity of the Aleutian low pressure system. Characteristics of the Aleutian Low have been linked to interannual fluctuations in the tropical ocean-atmosphere system (the El Niño/Southern Oscillation, ENSO) and interdecadal changes in the Pacific Decadal Oscillation (PDO). Both ENSO and the PDO affect the delivery of water to the Pacific Northwest (via precipitation and river runoff).⁴⁰ How will climate change affect the frequency or intensity of these climate oscillations? Will it alter their impacts on Northwest climate?

Past climate variability has been shown to cause a chain of impacts in the Pacific Northwest, beginning with the region's hydrologic cycle and spreading to affect the disparate areas of forests and rangelands, aquatic ecosystems, coastal activities, agriculture, human health, energy production and utilization, and urban centers. What follows is a summary of our current understanding of the ways in which each of these eight dimensions is vulnerable to future greenhouse gas-induced climate change. Many of these systems are already under a great deal of human-induced stress. While the additional stress brought by climate change may be small in comparison, the combination of climate change with past and current stresses may result in increased vulnerability. Incorporation of an understanding of regional vulnerabilities into management planning will be important, both to prepare for climate impacts and to minimize aggravation of such impacts by related human activities.

Quite apart from vulnerabilities, will climate change of the magnitude predicted create opportunities for and in the Pacific Northwest? Obvious examples exist in the realm of agriculture, where increasing temperatures may lengthen the growing season, increasing productivity in this region. Opportunities are also likely to arise in the arena of energy

production. The share of Northwest electricity provided by hydropower is likely to continue to decrease in the future, necessitating an increase in the amount of power provided by other sources. In view of the current international debate and the possibility of future regulation of CO₂ emissions, alternatives to fossil fuel-powered energy production and transportation may become increasingly attractive. This suggests openings for development of alternative energy sources and associated technologies as well as for the development of efficiency technologies.

HYDROLOGY & WATER RESOURCES

The Pacific Northwest is characterized by two types of river basins, or catchments, that will be affected differently by climate change. Rivers east of the Cascade mountains are primarily fed by spring snowmelt; wintertime mountain snow accumulation melts during the spring, causing flows that typically peak in early June. West-side river runoff is dominated by winter rains, augmented by spring snowmelt at higher elevations. Some Pacific Northwest rivers (parts of the Snake, for example) are fed heavily by ground water. Large rivers, such as the Columbia, have all these features.

The climate scenario for the Pacific Northwest projects precipitation increases during winter and decreases during summer. Increased temperatures imply that less wintertime precipitation will fall as snow and more will fall as rain, resulting in decreased snowpack accumulation, and therefore decreased water storage. Snowmelt would occur earlier in the year, due to warmer temperatures and the possibility of an increased frequency of rain-on-snow events. These climate changes would alter the flow patterns of snowmelt dominated rivers, shifting the period of peak runoff from springtime toward a rainfall-dominated peak in the winter. Flow patterns in rainfall-dominated rivers are likely to be amplified by climate change, with wintertime flows increasing and summertime flows decreasing. Consequences of these changes for water resource management include the need for more deliberate spillage in west-side rivers and the possibility for decreased water supply in summer, given reservoir storage limitations.

In order to understand these consequences more fully, the MPI climate scenario was used to run regional hydrologic and river reservoir models. It is important to note that current GCMs cannot provide the watershed-specific information or the details of future climate variability that are necessary to predict future hydrologic responses accurately. Future projections are also limited by lack of information on how climate change related vegetation changes would affect future basin water budgets and how future water and energy demands will change. Thus, these studies can be used to indicate what the projected changes in monthly average temperatures and precipitation would mean for Pacific Northwest water resources, given today's understanding and structure of the hydrologic system.

West-side rivers (Green River Case Study)

The temperature and precipitation changes predicted by the MPI climate scenario were applied to a hydrological model of the Green River, the source of Tacoma, Washington's water supply.³⁶ Results of this study may be generally applicable to similar rivers west of the Cascades. Annual runoff increased in the lower (rainfall-dominated) basin, particularly during the winter. As expected for a snowmelt-dominated system, peak flows in the upper basin shifted towards the winter. Summer and fall river runoff decreased substantially.

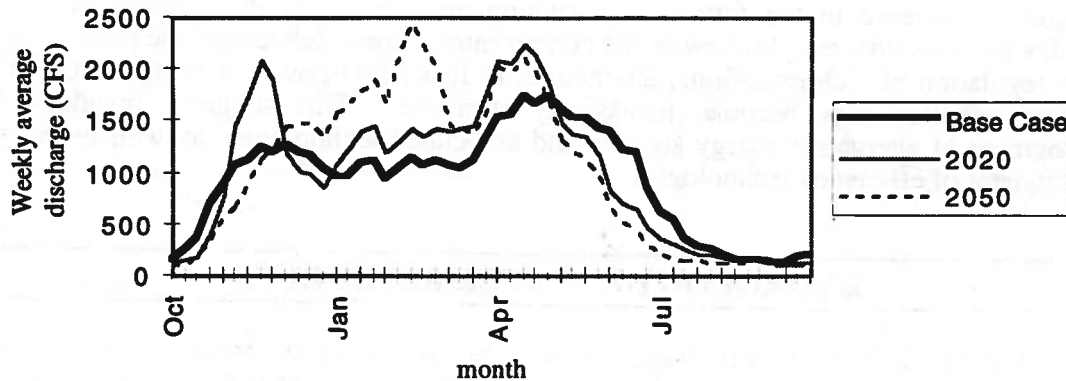


Figure 2. Average hydrographs for the upper Green River, Washington; base case and projections for 2020 and 2050. Vertical scale is weekly averaged river discharge in cubic feet of water per second.

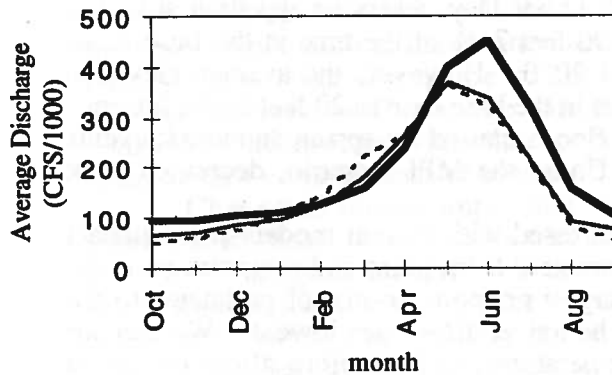
Climate change alone (without future demand growth caused by population increases) was found to have little or no adverse effect on either the performance of the Tacoma Water Department's water supply system or on system revenues. However, the number of times the system failed to meet instream flow requirements (relevant to fisheries protection) more than doubled in 2050, assuming that current rules for reservoir operations are followed in the future (*i.e.*, no adaptive management). Supplemental reservoir releases might be necessary to mitigate the effects of lower flows, but would be unlikely to resolve the issue given current Tacoma Water Department water rights. In addition, climate change resulted in a considerable increase in flood frequency. Mitigation of the larger flood peaks that would occur under a warmer climate may not be possible within the constraints of the existing physical infrastructure. How will climate change affect uncontrolled river systems directly affected by short-term flooding events?

The Columbia River Basin

The Columbia River is the fourth largest river in North America. It drains catchments in Washington, Oregon and Idaho, as well as Montana, British Columbia and Nevada. Regional growth, as well as changing water allocation priorities, are increasingly stressing the river system. According to the three major Columbia River operating agencies, "there is simply not enough water flowing in the system to meet all the demands. Trade-offs must be considered...in recent years, demands by the various users of the river have increased dramatically, resulting in increasing conflicts among users."⁶

Under the MPI climate scenario, the Columbia River Basin, which is currently a snowmelt-dominated system, would experience a shifting of peak flows toward a winter rainfall-dominated peak.³⁷ In the basin overall (represented by the Dalles, Figure 3A), average annual runoff would decrease and flow would peak one month earlier. Decreases in average runoff are driven by a decrease in average annual precipitation of ~10% over the basin. Upriver, where the Snake River joins the main stem (at Ice Harbor, Figure 3B), peak flows would decrease and spread over a period of several months. In general, flows would decrease throughout the Columbia River Basin during the low flow period of August-January. The hydrologic changes are extremely sensitive to the spatial distribution of future changes in precipitation; changes which -- under the MPI climate scenario -- do not occur uniformly over the Columbia River Basin.

3A. Columbia River Naturalized Flow at the Dalles



3B. Snake River Naturalized Flow at Ice Harbor

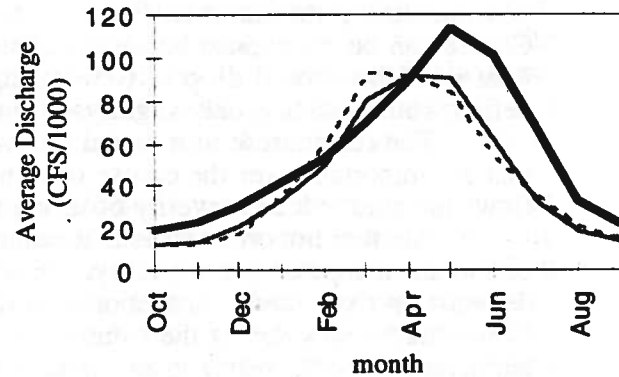


Figure 3. Monthly mean hydrographs for the base case (heavy solid line) and MPI climate scenario in decades 2020 (solid line) and 2050 (dashed line) for (A) the Columbia River at the Dalles and (B) the Snake River at Ice Harbor. Vertical scale is monthly averaged river discharge in thousands of cubic feet of water per second.

The projected shifts in runoff timing and changes in average streamflow will have implications for energy production, fish protection and irrigation water supply.²⁷ The changes in seasonal timing of runoff associated with the warmer climate scenarios tend to be advantageous for hydropower production in February and March, a period of high demand, but may jeopardize subsequent reservoir refill and hydropower production for the following year. Under the MPI scenario, failure to meet firm-energy production requirements occurred more often, were larger and lasted longer. The reliability* of the system to meet firm-energy production requirements was found to decrease from 96% in the modeled base case to 82% in 2050, while the average magnitude of shortfall increased by a factor of approximately 8.5. If the MPI scenario were to occur, there probably would be a need for additional power sources to supplement hydropower.

Hydropower system managers use the concept of the "critical period," the three-year period of lowest extended flows in the historical record, to determine the hydro system's firm energy capability and rules for system operation. Will the current critical period used for system planning be relevant in the future? How might future climate change and climate variability affect the Columbia River system's vulnerability to drought?

The projected decreases in streamflow have negative implications for fish protection. The reliability of meeting the minimum flow requirements set by the 1995 National Marine Fisheries Service Biological Opinion⁴¹ for McNary Dam on the main stem of the Columbia dropped from 85% in the base case to 76% in 2020 and 74% in 2050. These flow requirements are difficult to meet today, due to the limited storage available to support them, and become more difficult to meet under the MPI scenario.

Over seven million acres of agricultural land in the Columbia River Basin rely on irrigation water from the Columbia. Current irrigation demand cannot always be met in heavily allocated basins like the Snake and the Yakima. The model explored the reliability of meeting a fixed irrigation demand (90% of 1989 demand) under the MPI climate scenario. This reliability would decrease from 97% in the base case to 84% in 2020 and 2050 in the upper Snake River basin. Demand reliability in the middle Snake would decrease from 86% to 70%. Would decreased ability to meet demand from surface sources result in increased groundwater pumping? How would that impact long-term river flows and groundwater quality?

* Reliability is a measure of the hydropower's system to meet demand. A reliability of 96% means that the system met demand 96% of the time and failed 4% of the time.

To accommodate recreational use of the Columbia River Basin system, dam operators try to keep storage reservoirs that are used for recreation as full and stable as possible during the summer. For June 1 through Labor Day, reservoir elevation at Grand Coulee can be maintained between 1285 and 1290 feet 74% of the time in the base case. That reliability would drop to 67% in 2020 and 2050. However, the average elevation deficit would increase only slightly -- from 19 feet in the base case to 20 feet in the future.

The current reservoir model can evaluate floods caused by spring snowmelt events that are important over the course of a month. Under the MPI scenario, decreased peak flows indicate reduced severity of spring floods.

Another important issue that cannot be addressed with current models is the impact of climate change on water quality. Dilution of wastes, from point and nonpoint sources, depends on river flows. Irrigation runoff, the largest nonpoint source of pollutants to the Columbia,⁷ peaks during the summer months when river flows are lowest. Warmer air temperatures could result in increased river temperatures, and therefore affect dissolved oxygen concentrations in some lakes and tributaries. How will these changes affect fish populations? Will climate change impacts on water quality be significant?

The reliability of meeting the demands of major uses -- hydropower production, fisheries protection and irrigation supply -- are projected to decrease under the MPI climate scenario. This suggests that either changes to the management system will be required to operate the system more effectively, or that the system's goals would be met less frequently in the future. If climate changes in a manner similar to that predicted by the MPI scenario, increased competition for resources among major users of the river seems inevitable. How would a diverse and fragmented management system cope with increased competition? Could water demand be managed in such a way as to reduce potential conflicts and/or system failures? Will the system be more or less sensitive to changes in future variability? Will the diverse management groups of the Columbia River Basin be flexible enough to respond to the increased uncertainty due to climate change?

FORESTS & RANGELANDS

The distribution of tree species and the composition of ecosystem communities in the forests of the Pacific Northwest are tied to the climate of the region, particularly to moisture availability. Past variations in climate have been shown to alter forest carbon budgets (through tree growth and carbon sequestration), shift forest composition along environmental gradients, and alter disturbance regimes.²⁵ Forests are most strongly linked to climate during regeneration, and through climate's impact on disturbances. It is through these links that the impacts of future climate change will be manifested most clearly.²⁵

Forests will be directly impacted by temperature and precipitation changes as well as by increased levels of atmospheric CO₂. Photosynthesis, respiration and other important physiological processes are directly affected by temperature and moisture regimes.²⁵ Forest productivity in many parts of the Pacific Northwest is particularly sensitive to available moisture. As temperature increases, the moisture available for plant growth will decline, even with no change in precipitation. Projected summertime decreases in precipitation are likely to intensify the typical Pacific Northwest summer dry period. Benefits of increased CO₂ (increased water-use efficiency, growth rate, productivity and nitrogen-use efficiency) have been observed in seedling studies, but may not apply to mature plants in the field and are still quite controversial.³³ In addition, species are likely to adapt to increased levels of CO₂ over time and ecosystems may reach carrying capacities imposed by other limits.⁴

The vegetative shifts likely to result from climate change are difficult to predict with specificity. Although a climate warming of 2.5°C (4.5°F) has been likened to a shift of climatic zones 100-250 km (60-150 miles) northward or 500-600 m (~1800 feet) up in elevation, forest ecosystems are not expected to shift as intact communities. In general, warming may cause earlier snowmelt, lengthening the growing season at cool, wet, high

elevation sites, making them more hospitable to trees in the future. Lower elevation, currently dry locations (on the lower east slopes of the Cascades, for example) are likely to become inhospitable to forests in the future.²⁵ Redistribution of tree species will depend on the new combinations of temperature and precipitation that are likely to result from climate change. Tree species response to these changes is likely to be highly individualistic. Species response will also be site-dependent, varying with elevation, aspect and competitive interactions with other species. The combination of these factors is likely to result in new combinations of species.⁴⁶

Changes in forest composition or location would be slow to occur in the absence of other disturbances. Mature trees tend to be long-lived and resilient and can survive long periods of marginal climate.⁹ It is during the stage of tree regeneration, or seedling establishment, that forests are most vulnerable to climate change.²⁵ Seedlings are especially sensitive to temperature and may not be able to establish and grow under altered climatic conditions. Because climate zones are likely to shift faster than natural tree migration rates,^{15,29} established adults of appropriate species and genotypes will be separated from the location where seedling establishment is needed in the future.

Climate change is likely to increase the frequency and/or the intensity of disturbance regimes, such as wildfires and pest outbreaks. Such disturbances will act to hasten the otherwise slow response of established forests to climate change. Regions of increased summer drought will experience increased risk of fire, perhaps extending hazard into areas not now affected, especially where forests are dead or already stressed by drought or pests.³³ Fires may initially be of higher intensity, due to the increase in forest biomass resulting from fire suppression activities during much of the 20th century.² Increased temperatures are likely to allow forest pests, such as the balsam woolly adelgid, to expand their ranges into higher-latitude or higher-altitude environments from which cold temperatures currently exclude them. Warming will also enable some insects to complete more generations per year. Direct climate stresses, such as drought, can also make forests more susceptible to pest attack.³³ Mono-specific stands common to many forestry practices are particularly vulnerable to outbreaks of pests and diseases.³³ Disturbances may be followed by atypical patterns of succession with early domination by weedy annual plants, exotic species, or fast-growing early successional hardwoods.^{45,46}

In light of these impacts of climate change, several questions need to be addressed. Do current forestry management plans adequately encompass the possibility of climate variability and change? How will climate change impact forest productivity overall? What threshold of combined stress can forests withstand? If changes aren't gradual, but occur suddenly, will managers be able to cope/respond? How should national parks -- with their fixed borders and moving ecosystems -- be managed?

Rangelands of the Pacific Northwest are characterized by sagebrush shrub steppe and pinyon-juniper woodlands. Because of the high correlation between rangeland types and climatic zones, future changes in temperature and precipitation are highly likely to result in changes in rangeland boundaries.²⁹ Rangelands are also characterized by large temperature and precipitation extremes; small changes in variability or in extreme events may have disproportionate effects on rangeland productivity, with precipitation changes considered most important.²⁹ How will changes in future precipitation and/or temperature variability be magnified in rangeland ecosystem response? Will future changes be bigger than the swings currently observed?

Increased atmospheric CO₂ may result in decreased forage quality by increasing plant C:N ratios.³ Increased CO₂ could also change the competitive relationships of some range ecosystems in favor of some exotic grasses.⁵⁴ Future rangeland boundaries and ecosystem types will also be influenced by wildfires which may increase with increased exotic invasion and/or a drier climate.

Current human activities on rangelands alter the hydrological cycle, plant species' abundance and distribution, and soil erosion and may constitute equal or greater changes than those induced by future climate change.³ How much plasticity is present in the current

system? Will significant adaptive management response be required to maintain rangelands in a productive state?

AQUATIC ECOSYSTEMS

The aquatic and marine ecosystems of the Pacific Northwest are a regional economic, cultural and recreational resource. Many of these ecosystems are currently stressed by historical over-harvesting, pollution, habitat losses, hatchery practices and dams. Climate change is likely to cause increased stress to many of these systems.

In general, freshwater fisheries (especially in small rivers and lakes) are expected to be most vulnerable to climate change. Estuarine fisheries, particularly those impacted by sea level rise and decreased river flow, will be next most sensitive. High seas fisheries are expected to be the most robust to climate change.²⁰

Climate change impacts to freshwater ecosystems will primarily result from hydrological changes. The decreases in summer and fall runoff and the increased failure to meet minimum instream flow requirements that are predicted for controlled west-side rivers as a result of the MPI climate scenario* could negatively affect salmon migration and spawning. The predicted increases in flooding and wintertime runoff would alter sedimentation patterns, possibly harming fish habitat and decreasing egg-smolt survival.¹² High flows could also increase egg mortality. Changes in river flow patterns will affect smolt out-migration and survival¹², but the specific impact is difficult to predict. Climate change will also impact freshwater lakes by altering connectivity with other bodies of water, changing mixing regimes and therefore impacting dissolved oxygen content.²⁰

Increased temperature in freshwater bodies will affect the survival, reproductive capacity and growth of fish. It may result in increased mortality via increases in disease, predation and the energetic demand of migration.²⁰ Warming is expected to result in a general northward shift of freshwater species.²⁹ Those populations currently living at the extremes of their ranges are most susceptible to change. Temperature increases have been shown to alter the timing of migratory return in anadromous species that can adapt to altered river temperatures: Columbia River shad return currently occurs 38 days earlier than in 1938, in response to the earlier spring warming of the river.⁴⁸

A modeling study examining the implications of a (2°C) warmer and (35%) drier climate for salmonids in the Columbia River Basin⁴² suggested that steelhead, which can tolerate warmer temperatures and intermittent stream conditions, and lower-basin fall chinook and coho could benefit from the changes in streamflows and temperatures associated with such a climate change. On the other hand, sockeye and spring and summer chinook would be adversely affected, due to warmer lake temperatures (sockeye) and earlier timing of peak river flows (chinook). However, this study may neglect the considerable capacity of fish to maintain core body temperature by finding areas of cool water within the river.⁵

Climate change will also impact estuaries and coastal areas which provide important habitat for outmigrating salmon, spawning grounds for some oceanic species, and feeding, nesting and breeding habitat for various animals and shorebirds. Accelerated sea level rise (discussed in the following section, *Coastal Activities*) is likely to cause permanent loss of habitat as low-lying coastal areas are increasingly squeezed between rising water levels and shoreline development. Coastal areas will also be impacted by any changes in nutrient supply caused by alterations of offshore upwelling processes. Long-term natural climate variability is also known to affect mixing processes in large coastal basins such as Puget Sound, altering nutrient supply.¹⁶ How would projected decreases in freshwater runoff affect the dynamics of Puget Sound? What implications will that have for local fish stocks?

* see *Hydrology & Water Resources* and Lettenmaier, et al. 1995.

Climate change impacts to oceanic fisheries (and to the oceanic life-phase of anadromous stocks) are difficult to predict, due to considerable uncertainty about the physical changes that climate change will induce in the ocean. GCMs best predict future changes in air temperature, but these changes are not nearly as important to oceanic ecosystems as the larger physical forcing factors of winds, currents and ocean mixing. The results of climate change on physical ocean dynamics, including coastal upwelling rates and mixed layer structure cannot currently be predicted.

In addition, the link between past climate and fisheries production is complicated and difficult to disentangle from impacts caused by human activities. Retrospective studies have provided evidence that climate variability impacts fishery productivity on both the interannual (ENSO) and interdecadal (PDO) time scales. Past climate variations have led to restructuring of oceanic ecosystems, and perhaps alteration of the oceanic carrying capacity for some species.^{24,32,50} The PDO regime shift of 1976-77 provides a good example of how a past climate change has significantly altered oceanic ecosystems. Intensification of the Aleutian atmospheric low pressure center resulted in a transition to cooler than average sea surface temperatures in the central North Pacific and warmer than average temperatures along the NE Pacific coastline.⁴⁰ This climate shift resulted in dramatic shifts in salmon production regimes throughout the Pacific Ocean; salmon production in Alaska has been at historical highs since the climate shift, while that in the Pacific Northwest has been near historic lows.⁴⁰

Climate change is thought to impact oceanic ecosystems from both the "bottom-up" and the "top-down."²⁴ Changes in advective processes affect primary and secondary oceanic productivity,^{32,50} impacting higher trophic levels through changes in the timing, species mix and distribution of food supply. Stock recruitment will be affected through redistribution, loss, or mortality of eggs and larvae. Temperature changes will also impact fish stocks directly, by impacting fish metabolism rates (especially for larvae and juveniles²⁴), reproductive cycles, migratory timing and patterns, and species ranges.⁵³ Birds and marine mammals will primarily be impacted through changes in food availability and abundance.²⁴

If climate change impacts on oceanic ecosystems result in increased mortality for anadromous species, efforts to improve stock survival would need to focus on their freshwater and estuarine environments, areas most closely linked to human control. Are the dynamics of fish survival sufficiently understood to enable intervention? How would such efforts coordinate or collide with efforts to respond to climate change impacts on other dimensions (hydrology/water resources or forestry, for example)? How can predictive capability for evaluating the impacts of climate change on oceanic ecosystems be developed?

COASTAL ACTIVITIES

Climate change will be manifested in an accelerated rate of sea level rise, due to thermal expansion of the oceans and increased melting of glaciers and ice caps. The current best estimate of future sea level rise is 50 cm (20 inches)^{*} by 2100 (with a range of 20-86 cm), which is much larger than the increase of 10-25 cm that occurred during the past century. In the short-term, sea level rise predictions are more certain^{**}: about 7 cm by 2020 and 20 cm by 2050. These predictions are based solely on estimates of human-caused climate changes and they are likely to be underestimated.⁵⁶

* To convert centimeters to inches, divide by 2.54.

** Short-term predictions reflect changes already induced to the global climate system and do not depend on projections of future greenhouse gas emissions.

Local sea level change is modified by vertical land movements; where land is subsiding, relative rates of sea level rise will be higher than average, while areas of land uplift will experience smaller changes in sea level. In Washington state, land subsidence makes the South Puget Sound region particularly vulnerable to accelerated sea level rise.⁵¹

Other potential impacts to the coastal zone include changes in ocean wave characteristics, coastal upwelling dynamics and any alterations in the frequency and intensity of winter storms. The impact of climate change on these processes cannot be accurately predicted at this time.

Anthropogenic processes such as coastline armoring, wetland filling, logging, agriculture, dredging, exotic species introductions and other disturbances have had a far greater impact on the coastal zone than past climate-related impacts. While future climate change is unlikely to supersede these effects, it represents an additional stress to systems already under a great deal of development and population pressure. Accelerated sea level rise is likely to aggravate existing coastal management problems, including erosion and landsliding, flooding of low-lying areas, decrease in wetland areal extent and saltwater intrusion.⁵¹

Higher sea levels provide a higher base for storm surges, leading to increased flooding potential. Soil saturation may also result from a rise in the groundwater table, limiting water runoff during floods. The higher sea levels that currently occur during winter (vs. summer) and during El Niño (vs. non-El Niño) years may increase current flood risk during those times, but are not necessarily accounted for in current risk assessment.²² The City of Olympia, WA found that the most serious risk posed to the city by future sea level rise is the potential increase in the frequency and severity of flooding to the port and central downtown areas.¹³ What are the risks of incorrectly assessing periodic flood magnitude both now and in the increased flooding regime of the future?

Increased coastal erosion is also likely, both within Puget Sound and on the outer coasts of Washington and Oregon. In interior waters, landslides and bluff failures result from heavy winter rains, which may increase, and from undercutting by extreme tides and storm surges. On the Pacific Coast, severe storms leading to extreme erosion events have often coincided with El Niño events (and its associated higher sea level) during the past several decades.³⁴ Sandy beaches throughout Oregon and in Southwest Washington are especially vulnerable to erosion. If climate change also results in altered ocean storm dynamics, future coastal patterns of accretion and erosion may substantially change.³⁵ Current increases in beach erosion rates from Gray's Harbor south to the Columbia River have been linked to the loss of sediment supply from the Columbia River.⁴⁷ Erosion has also begun in previously stable or accreting parts of Washington, such as Leadbetter Point and Ocean Shores.^{10,47,55} Areas such as these will be particularly vulnerable to climate change-induced increases in coastal erosion.

Sea level rise will also result in inundation of low-lying coastal areas and wetlands. Parts of Highway 101 in Oregon are likely to be flooded and may need to be moved with a 30 cm (1 foot) rise in sea level.⁴³ Coastal wetlands may be increasingly squeezed between rising seas and existing or planned human developments, resulting in loss of habitat for migratory birds, fish, shellfish and water fowl.

Coastal hardening - protection of shoreline property by bulkhead construction or other armoring - has increased dramatically over the past 20 years. In one study along the Oregon coast, shoreline protection and hardening has been shown to be related to ENSO-related winter storm activity.²⁶ Such hardening causes habitat loss, loss of shoreline wetland and/or riparian vegetation, loss of migratory corridors, loss of large organic debris and supplies for accreting landforms as well as loss of spawning habitat.⁵² Significant institutional barriers currently prevent effective control over the rate of coastal hardening in Washington and Oregon.* As hardening trends continue, and are perhaps accelerated by

* Single-family residential construction and residential shoreline erosion-control structures are exempt from the requirement for a Shoreline Substantial Development permit in Washington state. See also Good, 1994.

relative sea level rise, detrimental changes in physical and biological processes may be expected to occur with increasing frequency. How can the motivation for property protection be balanced by other concerns in the coastal zone? Can the process of coastal management be improved to account for such concerns?

Other impacts of climate change on the coastal zone include increased seawater intrusion into coastal freshwater aquifers, disruption of the operation of coastal storm drains, altered sewage treatment plant outfall hydraulics and increased possibility of groundwater contamination by landfills and underground hazardous waste tanks. Coastal ecosystems may also be altered by water column warming and salinity changes.

AGRICULTURE & GRAZING LANDS

As a whole, US agriculture is not considered vulnerable to climate change. It is at the regional level, rather than in the national aggregate that impacts of changing temperature and precipitation patterns and increased levels of atmospheric CO₂ are likely to be felt.¹

Higher temperatures may lead to crop heat stress and decreases in yield stability,¹⁸ especially for crops with specific temperature requirements, such as corn, soybeans and wheat which are sensitive to high temperatures during blooming.¹⁸ Changes in day-to-day and year-to-year temperature and precipitation variability (changes which cannot currently be predicted) will also impact crop yields. However, warmer temperatures may benefit Pacific Northwest agriculture by extending the growing season. Double-cropping would become possible for some crops in Eastern Oregon if the growing season lengthened by only 20 days.⁴³

Increased temperatures are likely to increase demand for irrigation water.^{23,30} This may be a problem in heavily allocated water basins such as the Snake and the Yakima. If climate changes as indicated by the MPI climate scenario, the reliability of the Columbia River Basin system to supply irrigation water demand (given current physical and management constraints) will decrease significantly.* West of the Cascades, increased soil saturation and flooding in low-lying river valleys may negatively impact agriculture there.

Increased levels of atmospheric CO₂ have been found to have a positive effect on crop growth and yields of plants such as wheat and soybeans with a three-carbon (C3) photosynthetic pathway.⁴⁹ This effect may counteract negative implications of temperature and precipitation changes,⁴⁴ although the amount and sustainability of the benefit depend on temperature and precipitation (both of which will change), as well as crop species, nutrient availability, and soil quality. Increased CO₂ will also benefit growth of C3 weeds. In addition, plants grown in higher levels of CO₂ may have less nutritive content (higher C:N ratio), causing increased feeding by pests such as the soybean looper³⁸ and/or increased mortality of pest larvae.²¹ Temperature increases may expand the ranges of agricultural pests and/or accelerate their life cycles. For example, warming may result in up-valley expansion of orchard pests that are currently confined to lower elevations in fruit-growing regions of eastern Washington.

Livestock production will be affected by changes in grazing and pasture productivity. Some vector-borne livestock diseases may increase, similar to vector-borne human diseases. Increased winter temperatures may decrease the incidence of livestock respiratory disease.¹⁸ Intensively managed livestock systems such as those in North America are thought to have more potential for adaptation than crop systems.⁴⁹

Any attempt to assess the implications of this suite of impacts to regional agriculture must consider multiple system interactions and feedbacks. Will climate change affect optimal planting and harvesting dates? How will farmers and the agricultural infrastructure adapt to limit losses or adjust to take advantage of improved climatic conditions? Will

* see *Hydrology & Water Resources* and Hamlet et al., 1997.

climate changes be gradual enough for farmers and technology to adapt? How will climate-driven changes in the rest of the world impact the Pacific Northwest's export-driven agricultural sector? If climate change increases pest problems, how will farmers respond in light of current pressure to limit chemical usage?

HUMAN HEALTH EFFECTS

Warmer temperatures are known to increase photochemical smog production. The warmer, drier summers predicted for the Pacific Northwest may also result in elevated pollen counts. Because smog build-up and removal over urban areas is determined by weather patterns, urban air pollution could change in the future. Increased air pollution will impact infants and small children as well as all those with preexisting respiratory or cardiac diseases.³⁹ One study predicts that climate change could increase wintertime mortality in Seattle due to increased incidence of high-risk air masses. This study projects a small decrease in Portland, Oregon. Summertime mortality decreases slightly in Seattle and increases somewhat in Portland.³¹

Climate change could result in an increase in vector-borne diseases. Increased temperatures and/or altered rainfall patterns may allow vectors to expand into higher-latitude or higher-altitude environments from which they are currently excluded. Warming could also enable some insects to complete more generations per year, increasing the potential for outbreaks.^{29,57} How will climate change affect vector populations in this area? Will the relatively rare vector-borne diseases of arthropod-borne encephalitis, Yersiniosis, hantavirus or lyme disease increase in the Pacific Northwest? Infectious and vector-borne diseases (such as malaria, cholera and dengue fever) are highly likely to increase throughout the tropics and into the southern US.⁵⁷ How will the Pacific Northwest be impacted by disease transmission via travelers from other parts of the world?

Climate change may also result in water-borne health problems. Sea level rise may cause contamination of drinking water by salt-water intrusion. This is already a problem in parts of the region and one of the City of Olympia's concerns with respect to sea level rise.¹³ Increasing water tables may also cause increased contamination from underground hazardous materials storage tanks.¹¹ Leakages from onsite sewage disposal systems are a widespread problem that has led to closing of shellfish beds throughout Puget Sound and in Willapa Bay.¹¹ Warmer temperatures may also result in an increase in freshwater cyanobacteria in open calm expanses such as lakes or reservoirs.¹⁷ If sea surface temperatures increase, an increase in the frequency of paralytic shellfish poisoning (PSP) events is possible; exceptional PSP outbreaks on the Washington coast seem to be correlated with higher than average sea surface temperatures.¹⁹ Decreased streamflow in smaller rivers may result in inadequate dilution of instream wastes.

How will new seasonal patterns of temperature and precipitation affect diseases such as influenza that seem to be related to current climate patterns? How will warmer temperatures affect patterns of emerging infectious disease? Will the public health infrastructure be prepared to address these risks?

ENERGY PRODUCTION & UTILIZATION

Increased regional temperatures would decrease energy demand for winter space heating, but increase the demand for summer cooling. The net demand shift is difficult to predict. One study suggested that the annual heating and cooling load in commercial buildings in Seattle might increase by one-third as a result of the climate change associated with a doubling of atmospheric CO₂ (expected to occur during the second half of the 20th

century), but the single family home heating and cooling load could decrease by more than one-fourth.⁴³ Will population growth overwhelm climate change related demand shifts?

Transportation uses constitute another major component of energy consumption in the Pacific Northwest, as in the US as a whole. Direct climate change impacts to the transportation sector are likely to be small in this region.

The Pacific Northwest is highly dependent on hydropower (hydropower provides ~70% of the region's electricity⁴³). Hydropower production is highly dependent on climate. If climate changes as projected by the MPI climate scenario, the reliability of meeting current firm and non-firm energy production requirements in the Columbia River system would decrease significantly (see *Hydrology & Water Resources*). The reliability of producing firm energy requirements would decrease from 96% to 89% in 2020 and 82% in 2050. Non-firm energy reliability would decrease from 96% to 88% in 2020 and 86% in 2050. If the MPI scenario were to occur, there probably would be a need for additional power sources to supplement hydropower.

The effect of climate change on regional energy production besides hydropower is likely to be indirect. Coal-fired power plants may be increasingly affected by future regulations of CO₂, SO₂ and/or N₂O emissions. Thermal generating plants and combustion turbines operate less efficiently in warm weather and the former may require larger amounts of water for cooling.⁴³ Increased stream temperatures may decrease cooling efficiency.

Will regional hydropower supply and demand curves become more or less coincident in the future? What happens if summertime electricity loads change significantly during a time when hydro resources are limited? Will a larger proportion of Pacific Northwest power need to be imported from fossil-fuel burning power plants in other regions? How would increased temperatures affect electricity transmission line losses?

URBAN CENTERS

A consideration of the vulnerability of urban centers to climate change combines many of the potential impacts discussed in the preceding seven sections. Urban issues of population growth, economic health, water and energy supply and demand, waste disposal, public health and environmental conditions may all be impacted by climate change.

Population growth and economic health depend to some degree on the surrounding environment, either directly (via resource extraction or agricultural productivity, for example) or indirectly (quality of life). How will climate change impact Pacific Northwest cities' dependence on the productivity of their surrounding areas? How will the Pacific Northwest be impacted by migration to or from other parts of the country? How will economic changes wrought by climate change in the rest of the world affect the economy of the Pacific Northwest?

Climate change adds uncertainty to the process of planning for future energy and water demand. While the studies cited here found that municipal water supply is not likely to be adversely affected by the changes implied by the MPI climate scenario, the amount and timing of electricity supplied by hydropower is likely to change.* How can these factors be incorporated into future planning?

Wetter winters may contribute to increased flooding or landslides. What are the implications for floodplain development policies or local zoning ordinances? Could increased winter rains overwhelm some storm sewerage capacity? In Olympia, Washington, the water table is currently about a foot below the surface during the wet winter months.¹³ How would higher water levels impact structural stability of pavements

* see *Hydrology & Water Resources* and Hamlet et al., 1997

and building foundations? How will coastal cities deal with accelerated sea level rise and increased wintertime precipitation?

What changes will be required to the public health infrastructure to deal with climate change? Will the overall costs and concerns of climate change to cities be minor compared to continued population growth? Or will the combination of several climate-related impacts create a significant concern? Can urban planning be expanded to include the uncertainty introduced by future climate change?

TOWARDS AN INTEGRATED ASSESSMENT

This paper has discussed the ways in which eight dimensions of the Pacific Northwest, in turn, are vulnerable to climate change. A thorough evaluation of the vulnerability of each dimension would include an evaluation of how the eight dimensions interact. Where will climate change act to limit the supply or threaten the reliability of a resource on which several dimensions depend? What are the connections between the different dimensions, the linkages through which climate change-related impacts to one are felt in another? Will existing stresses and feedbacks between dependent or related systems combine to produce unpredictable responses to the additional forcing caused by climate change?

It is becoming evident that climate change will be manifested most directly in the Pacific Northwest through changes to the region's hydrologic cycle. Changes in water availability and in the timing of supply will impact all aspects of the region: forests, aquatic ecosystems, coastal activities, agriculture, human health, energy supply and urban centers. Thus water provides us with a framework for constructing an assessment of the impacts of global climate change on the Pacific Northwest.

The ultimate goal of a regional assessment is a simultaneous evaluation of the various vulnerabilities of a region, with an understanding of their associated linkages and feedbacks. It also requires an understanding of the opportunities provided by climate change. This report represents the first step in that direction. Until a regional assessment is complete, it will be important to expand our planning capabilities and management thinking in order to incorporate the risk and uncertainty imposed by future climate change into Pacific Northwest decision making and planning processes.

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