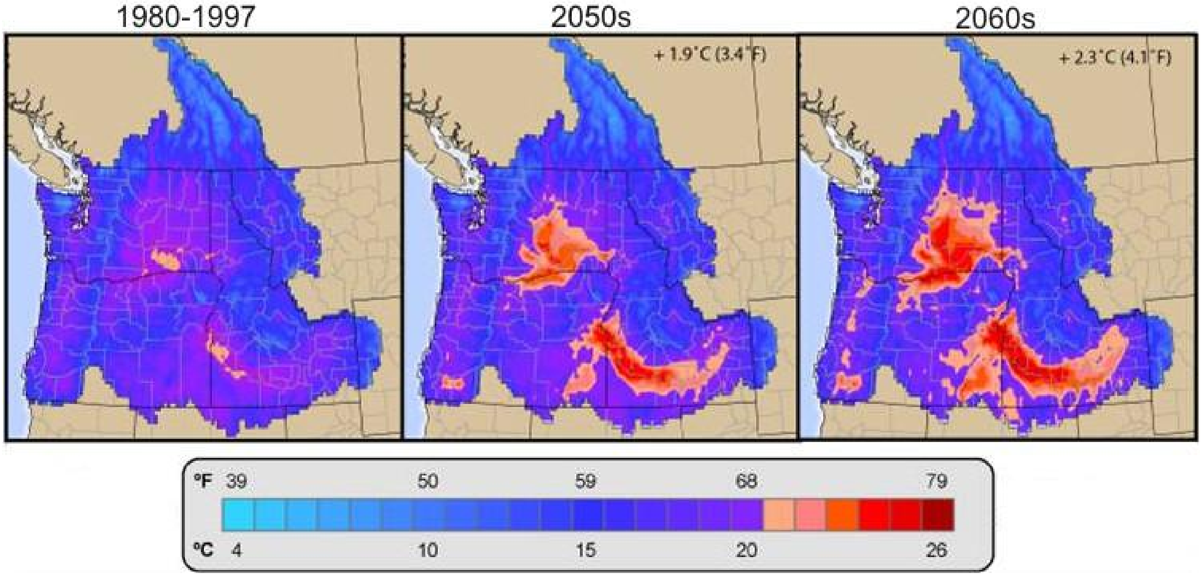
Independent Scientific Advisory Board

Climate Change Impacts on Columbia River Basin Fish and Wildlife



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ISAB Climate Change Report
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Cover graphic adapted from the University of Washington Climate Impact Group's graphic included as Figure 10 in this report.

Climate Change Impacts on Columbia River Basin Fish and Wildlife

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Executive Summary

Warming of the global climate is unequivocal. Evidence includes increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level. Eleven of the last twelve years (1995 -2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The linear warming trend over the last 50 years (0.13 +/- 0.03°C per decade) is nearly twice that for the last 100 years. The total global average temperature increase from 1850 – 1899 to 2001 – 2005 is 0.76 +/- 0.19°C.

Climate records show that the Pacific Northwest has warmed about 1.0 ºC since 1900, or about 50% more than the global average warming over the same period. The warming rate for the Pacific Northwest over the next century is projected to be in the range of 0.1-0.6˚ C/decade. Projected precipitation changes for the region are relatively modest and unlikely to be distinguishable from natural variability until late in the 21st century. Most models project long-term increases in winter precipitation and decreases in summer precipitation. The changes in temperature and precipitation will alter the snow pack, stream flow, and water quality in the Columbia Basin:

- Warmer temperatures will result in more precipitation falling as rain rather than snow
- Snow pack will diminish, and stream flow timing will be altered
- Peak river flows will likely increase
- Water temperatures will continue to rise

These changes will have a variety of impacts on aquatic and terrestrial habitats in the Columbia Basin.

Impacts of Climate Change on Fish and Wildlife Resources of the Columbia Basin

Changes already have been observed in many species' ranges, consistent with changes in climate. These range changes include poleward and elevationally upward movements of many insects, birds, trees, and forbs. Future climate change may lead to fragmentation of suitable habitats that may inhibit adjustment of plants and wildlife to climate change through range shifts.

Virtually all future climate scenarios predict increases in wild fire in western North America, including the Columbia Basin. Fire frequency and intensity have already increased in the past 50 years, and especially the past 15 years, in the shrub steppe and forested regions of the West. Drought and hot, dry weather already have led to an increase in outbreaks of insects in the Columbia Basin, especially mountain pine beetle, and insect outbreaks are likely to become more common and widespread.

Climate change in combination with expansion of human population will reduce and fragment wildlife habitats. Several community types and their associated wildlife populations are likely to decrease greatly in area, including alpine, subalpine spruce-fir, aspen, and sagebrush habitats.

Changes in hydrology and temperature caused by changing climate have the potential to negatively impact aquatic ecosystems in the Columbia Basin, with salmonid fishes being especially sensitive. The intensity of the effects will vary spatially. However, climate change can generate ecological responses in virtually all the tributary systems of the Columbia Basin. Several projections of the potential impact of climate change on cool and cold water fishes have been completed. One of these analyses suggests that temperature increases alone will render 2% to 7% of current trout habitat in the Pacific Northwest unsuitable by 2030, 5%-20% by 2060, and 8% to 33% by 2090. Salmon habitat may be more severely affected, in part because these fishes can only occupy areas below barriers and are thus restricted to lower, hence warmer, elevations within the region. Salmon habitat loss would be most severe in Oregon and Idaho with potential losses exceeding 40% by 2090. Loss of salmon habitat in Washington would be less severe, with the worst case about 22% loss by 2090. These estimates do not consider the associated impact of changing hydrology.

Climate change has the potential to affect most freshwater life history stages of trout and salmon. Increased frequency and severity of flood flows during winter can affect over-wintering juvenile fish and incubating eggs in the streambed. Eggs of fall and winter spawning fish, including Chinook, coho, chum, and sockeye salmon and bull trout, may suffer higher levels of mortality when exposed to increased flood flows. Higher winter water temperatures also could accelerate embryo development and cause premature emergence of fry. Bull trout require very cold, headwater streams for spawning. Therefore, a warming climate may disproportionately impact this species. Recent projections of the loss of habitat suitable for bull trout in the Columbia Basin as a result of climate warming range from 22% to 92%.

The construction of the hydrosystem has also altered mainstem hydrology and water temperature regimes. The changes in mainstem flows due to hydrosystem operations are substantially greater than the natural runoff changes, projected to be caused by climate warming in the 21st century. The changes caused by climate change will be similar to those changes already caused by operation of the hydrosystem. Currently, warming of water in the reservoirs begins earlier in the spring and persists longer into the fall than historically. Climate modeling of future water temperatures in the Columbia and Snake rivers predicts an increase of 1^{o} C or greater by 2040, adding to the increases caused by the hydrosystem.

Water temperature increases in the mainstem may impact Columbia River salmon in several ways. Increases in water temperature will accelerate the rate of egg development of fall Chinook, which spawn in the mainstem of the Snake and Columbia rivers, and lead to earlier emergence at a smaller average size than historically. Smaller sized fry are likely to have lower survival due to increased vulnerability to predators. Predation rates also will increase due to elevated water temperatures. Potential impacts of increased water temperatures on adult salmon include delay in dam passage, failure to enter fish ladders, increased fallback, and loss of energy reserves due to increased metabolic demand. Increases in mortality also may be caused by fish pathogens and parasites as these organisms often do not become injurious until their host becomes thermally stressed.

Changes in freshwater flow into the Columbia River estuary caused by climate change will be less than those caused by the hydrosystem. Nonetheless, some changes in estuary habitats may occur. Sea level rise in conjunction with higher winter river flows could cause the degradation of estuary habitats created by sediment deposition from increased wave damage during storms. Numerous warm-adapted fish species, including several non-indigenous species, normally found in freshwater have been reported from the estuary and might expand their populations with the warmer water and seasonal expansion of freshwater habitats. The potential impacts on salmon are not understood. Climate change also may affect the trophic dynamics of the estuary due to upstream extension of the salt wedge in spring-early summer caused by reduced river flows. The landward head of the salt wedge is characterized by a turbulent region known as the estuary turbidity maximum, an area with high concentrations of fish food organisms such as harpacticoid copepods. Changes in the upstream extension of the salt wedge will influence the location of this zone, but it is difficult to forecast the effect this change will have on juvenile salmon.

Scientific evidence strongly suggests that global climate change is already altering marine ecosystems from the tropics to polar seas. Physical changes associated with warming include increases in ocean temperature, increased stratification of the water column, and changes in the intensity and timing of coastal upwelling. These changes will alter primary and secondary productivity, the structure of marine communities, and, in turn, the growth, productivity, survival, and migrations of salmonids.

Earlier snowmelt and earlier, higher spring flows and warmer temperatures may cause spring Chinook and steelhead yearlings to smolt and emigrate to the estuary and ocean earlier in the spring. The early emigration coupled with a projected delay in the onset of coastal upwelling may cause the timing of ocean entry of juvenile salmonids to be suboptimal. The first few weeks in the ocean are thought to be critical to the survival of salmon off Oregon and Washington, so a growing mismatch between smolt migrations and coastal upwelling would likely have significant negative impacts on marine survival rates.

Changing ocean temperatures may alter salmon behavior, distribution, and migrations, increasing the distance to migrations from their home streams to ocean feeding areas. Energetic demands are increased at warmer temperatures, requiring increased consumption of prey to maintain a given growth rate. In addition, food availability in the ocean may be altered by climate change. Increasing concentrations of CO_2 in the oceans lowers pH, which reduces the availability of carbonate for shell-forming marine animals. Pteropods are expected to be especially impacted, and they can comprise up to 40% or more of the diet of some salmon species. If salmon migrate farther to the north and/or food is less available, longer times may be required to reach maturity, delaying the usual times of adult migrations into coastal water and rivers.

Including Climate Change in Columbia Basin Planning

In many cases, impacts of climate change on fish at one life history stage contribute to increased mortality at later stages; the impacts of climate change can propagate cumulatively through the life of the fish. In addition, climate change will occur concurrently with other impacts in the Columbia Basin. Studies that have examined the simultaneous effects of more than a single stressor (e.g., climate and land use; climate, land use, and human population growth) generally conclude that the effects of more than a single stressor are not easily predictable, but may often be more severe than simple combination of the single-factor outcomes. Planners will need to consider all factors likely to impact habitats in the Columbia Basin in the future to develop effective restoration strategies and prioritize actions.

Future impacts of climate change on fish and wildlife habitat in the Columbia Basin was poorly addressed in the subbasin planning process. The majority of plans acknowledged the general risk posed by global climate change but did not directly factor it into planning; about one quarter of the plans did not address climate change at all. Very few subbasin plans attempted to assess what future impact changes in climate might have on subbasin fish and wildlife populations and habitats and what effect these changes might have on the efficacy of proposed restoration measures.

Inclusion of climate change in planning processes has been hampered by several factors. In some cases, the information on climate change is very technical, making it difficult for planners to interpret it in a manner relevant to their planning process. The nature of climate change predictions also can be problematic. These predictions have generally been reported at very coarse spatial scales, making them difficult to apply to planning at the watershed or subbasin scale. However, climate-change projections at a scale compatible with subbasin planning are becoming more available, making analysis of this issue in future subbasin plans more tractable.

Mitigating Climate Change Effects

Only global strategies for reducing the emission of greenhouse gases will completely address climate change impacts on all habitats in the Columbia Basin. Dealing with this issue will require unprecedented cooperation among public and private land stewards and even among nations. As we seek solutions to these larger issues, the identification and implementation of actions that may offset some of the negative effects of climate change in the Columbia Basin represent the only near-term, local option for dealing with climate-change effects.

Climate change in conjunction with land-use changes has the potential to substantially reduce diversity in the basin by making many areas unsuitable for the native species that currently occupy these sites. The role of biodiversity in protecting both contemporary persistence and evolutionary potential of species is recognized in the Columbia River Basin Fish and Wildlife Program and in many other guidelines for mitigating the damaging effects of climate change. Locations that are likely to be sensitive to climate change and have high ecological value are sites where establishing adequate protective measures, including reserve areas, will be a key component of any effort to address changing climate in the Columbia Basin. Efforts to protect biodiversity and to prevent critical areas are already supported by the Fish and Wildlife Program, but actions have not yet been targeted to address climate change concerns.

In general, mitigating for changes in hydrology and temperature in tributaries that are caused by climate change will involve many of the same approaches that have been initiated in the basin to date. Any action that can help minimize water temperatures increases or augment stream flow during summer and autumn would contribute to this end. Specifically, protection of cold-water refugia for migrating salmon and restoration of riparian habitats in headwater reaches should have high priority. However, it is unlikely that there are any options to successfully deal with some of the projected changes. For example, there is little that can be done at a local scale to offset projected changes in elevation, accumulation, and melt timing of snowpack.

Global warming impacts on the mainstem Columbia and Snake rivers, estuary, and plume must be considered in the context of hydrosystem management. Because the hydrology and salmon habitat of the mainstem and estuary have been extensively transformed, managed, and manipulated for decades, there is a range of alternatives for mitigating climate change impacts on in these habitats. To the extent that hydrosystem operations are flexible, there are opportunities to mitigate for some climate change impacts in the mainstem, estuary and plume, because projected changes in natural runoff, even under the most extreme warming scenarios for the late 21st century, are substantially smaller than the changes caused by the development and operation of the hydrosystem in the late 20th century.

Possible actions that could be taken on the mainstem to address climate change impacts include:

- Flow augmentation from cool/cold water storage reservoirs. If this strategy requires addition storage capacity, careful consideration of the benefits and negative impacts of increasing the number of dams in the basin will be required.
- Use of removable surface weirs to reduce the time juvenile salmonids spend in the warm water of the dam forebays
- Reduce water temperatures in the ladders with water drawn from lower, cooler strata in the water column of the dam forebays
- Develop transportation strategies for initiating full transport of juvenile fall Chinook more focused on temperature criteria
- Evaluate the possibility of transporting immigrating adults through the lower Snake River when water temperatures reach near lethal limits in the late summer

- Expand the predator control program to introduced piscivorous species such as smallmouth and largemouth bass, walleye, and channel catfish
- Open backwater, slough, and other off-channel habitats along mainstem reservoirs and the estuary to encourage increased flow through these areas to help reduce water temperature and provide cool-water refugia

Climate change may delay the initiation of coastal upwelling in the spring, while earlier runoff and higher water temperatures may accelerate the emigration of smolts to the estuary and ocean. A mismatch between smolt migrations and coastal upwelling would likely have significant negative impacts on marine survival rates. Adjusting the timing of ocean entry by transportation or controlling the rate of downstream movement of in-river migrants could be evaluated as a possible option to ensure that ocean entry coincides with favorable ocean conditions.

If the ocean environment becomes less productive, density-dependent interactions will intensify, resulting in increased competition in the ocean. This may result in lower growth and survival rates for wild salmon. Reduction in hatchery releases during poor ocean conditions may enhance survival of wild stocks, but more research on this topic is needed.

Harvest managers need to adopt near- and long-term assessments that consider changing climate in setting annual quotas and harvest levels of fish from the Columbia Basin. For example, reduced harvest of stocks that are consistently below sustainable levels during poor phase ocean conditions could be allowed to recover their numbers and recolonize areas of freshwater habitat during favorable climatic phases.

The Northwest Power and Conservation Council and the Fish and Wildlife Program are well suited to address the challenges that climate change will pose for the fish and wildlife resources of the Columbia Basin. The efficient production, distribution, and consumption of power, especially power generated without the release of greenhouse gases, can contribute to global efforts to reduce human impacts on the greenhouse effect. Incorporating climate change into future fish and wildlife recovery plans can help to ensure that all reasonable measures are taken to buffer the natural ecosystems of the Columbia Basin from the changes in temperature and hydrology expected over the coming decades. The educational mandate of the Council provides a mechanism for encouraging the residents of the basin to become engaged in the type of coordinated effort that will be required to ensure that the progress that has been made in restoring fish and wildlife populations to date continues into the future despite a changing climate.

Climate Change Impacts on Columbia River Basin Fish and Wildlife

Introduction

There is compelling scientific evidence that we are living in a time of rapid, world-wide climate change. A recent report from the International Panel on Climate Change (IPCC 2007) illustrates the broad consensus among the scientific community about changes to the global climate. Climate changes include temperature, winds, rainfall, snow, ocean currents, and the interactions among these. Alterations in climatically driven processes will impact aquatic and terrestrial habitats in the Columbia Basin and the marine environments used by anadromous fishes from the basin. The resultant changes in habitat distribution and quality will affect most of the fish and wildlife populations in the basin.

The influence changing climate can have on the growth, survival, recruitment, and migration patterns of Columbia River salmon is amply demonstrated by the dramatic response of populations coast-wide to annual and decadal variations in climate and ocean conditions. Wild fire and severe insect outbreaks are both likely to increase in response to climate warming; both of these processes can fundamentally alter fish and wildlife habitats over large areas. Nonetheless, the impacts of climate change are rarely incorporated into natural resource planning in the Columbia Basin, despite the direction in the subbasin planning documentation that this issue be considered. Generally, the Council's fish and wildlife program and the NOAA Fisheries recovery strategies do not consider the impacts of climate change and implicitly assume stable conditions. However, the changes in regional snow pack, stream flows, and temperature in the Columbia Basin that are projected by most climate models could have a profound impact on the success of restoration efforts and the status of Columbia River fish and wildlife populations.

Some previous ISAB reports have touched on the subject of climate change. A section on climate and ocean change was included in the harvest report (ISAB 2005) and the tributary habitat report provided a brief discussion of climate change impacts on freshwater habitat (ISAB 2003). The treatment of this subject was superficial in these reports and a significant amount of recent scientific effort has been dedicated to better understanding the mechanics of climate change and the potential impacts. This report provides a much more thorough examination of the issue.

In this report we review the basic physics of the natural greenhouse effect, the role of past, present, and future human actions in altering the natural greenhouse effect, and how the resultant climate changes may affect the Columbia Basin. The potential impacts of these predicted climate changes on the aquatic ecosystems utilized by Columbia River salmon and other cool-water species and effects on the productivity of the salmon populations are explored, as are potential impacts on terrestrial ecosystems. Finally, we offer some suggestions as to how climate change might be incorporated into plans for ecosystem restoration and salmon recovery in the Columbia Basin and indicate some possible mitigation measures.

Much of the vocabulary that has evolved around the climate change issue is specialized to this field. Therefore, a glossary has been provided (Appendix A) that defines many of the technical terms used in this report.

The Greenhouse Effect and Human Caused Global Warming

The Greenhouse Effect

The Greenhouse Effect is an essential, natural part of the Earth's climate system that makes our planet remarkably hospitable for life as we know it. Earth's atmosphere, where clouds are absent, is nearly transparent to the visible radiation (light) that carries the bulk of the energy coming from the sun. Clouds and bright surfaces, like snow cover, reflect about 30% of the total incoming energy from the sun back to space, a smaller fraction is absorbed by the atmosphere, and the rest is absorbed by the Earth's surface. The absorbed solar radiation warms the Earth's surface, and because the Earth's surface is much cooler than the sun, its heat is radiated upward to the atmosphere at much longer *infrared* wavelengths. Because of trace gases in the atmosphere, such as water vapor, carbon dioxide (CO_2), methane, nitrous oxide, ozone, and a host of industrial chemicals, a substantial fraction of the infrared radiation from the Earth's surface is absorbed and warms the atmosphere (Fig.1). The higher atmospheric temperatures lead to an increase in atmospheric emissions of infrared radiation both upward to space and downward back to the Earth's surface where it is again absorbed, raising the Earth's surface temperature, and re-emitting radiation back to the atmosphere. This trapped infrared energy warms both the atmosphere and the Earth's surface substantially – surface temperatures without our natural Greenhouse Effect would be an icy 33 ºC (60 ºF) cooler than they are today.

Because increased concentrations of greenhouse gases cause a reduction in the infrared radiation passing freely from the Earth's surface through the atmosphere to space, this also causes increases in atmospheric and surface temperature until a net energy balance between incoming solar radiation and outgoing infrared radiation is achieved. Changing concentrations of aerosols in the atmosphere also cause a suite of changes in regional and global scale aspects of the Earth's energy balance. Large changes in aerosol emissions in the past century are also important factors in recent patterns of global climate change.

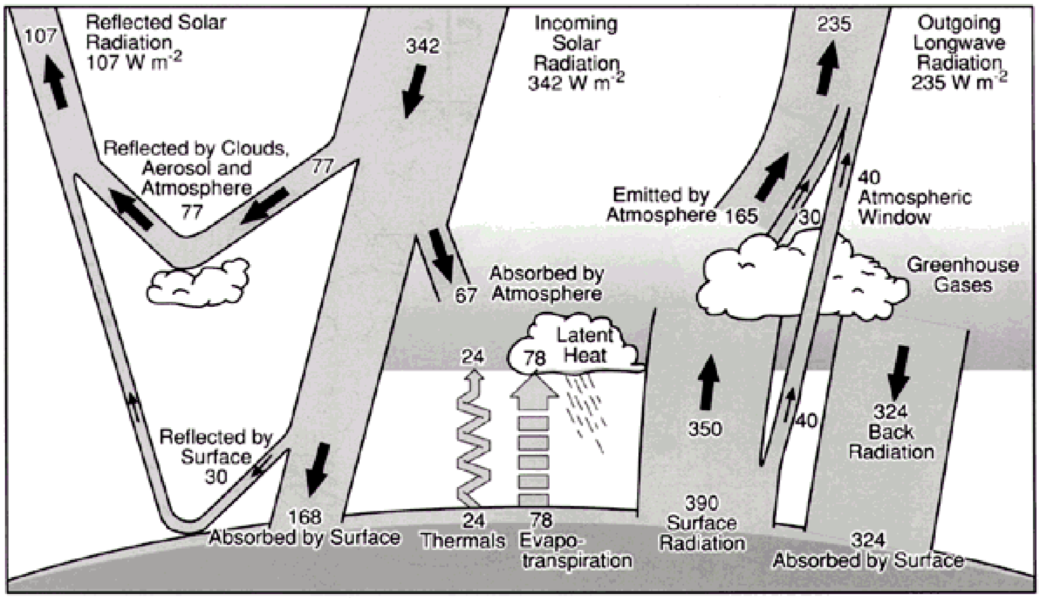


Figure 1: The Earth's annual energy budget in Watts per meter squared. Reproduced from Kiehl and Trenberth (1996)

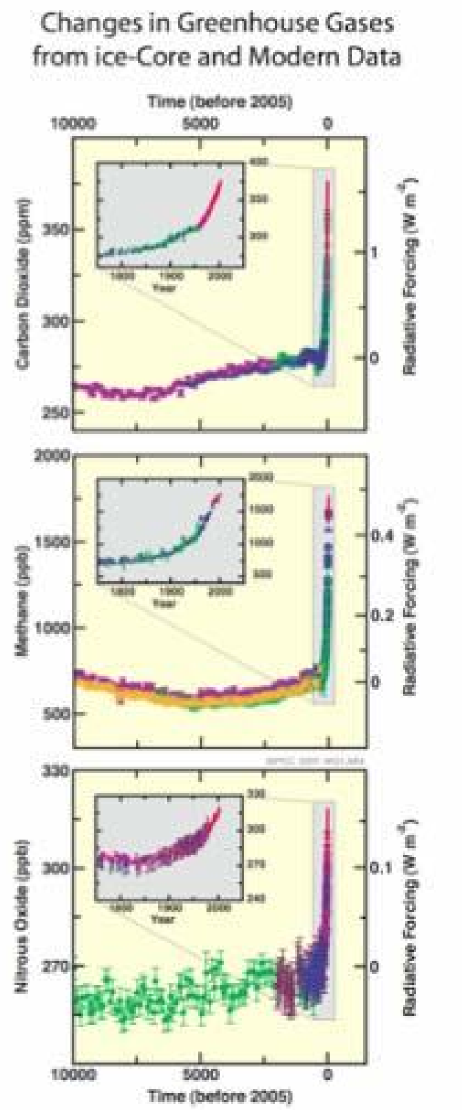
Human Caused Changes in Atmospheric Composition -- Greenhouse Gases and Aerosols

Global warming refers to a globally averaged increase in the near-surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences. Today, this term is commonly used as short-hand for *Anthropogenic Global Warming*, a phrase that refers to the observed and expected impacts of human-caused increases in the strength of the natural greenhouse effect (IPCC 2007). This current common usage of *global warming* applies to the remainder of this report.

The intensity of the natural greenhouse effect has varied over geologic time, with very warm eras coinciding with periods of abundant atmospheric greenhouse gases and cool eras coinciding with periods of relatively low levels of greenhouse gases. During the most recent ice age, which ended about 12,000 years ago, atmospheric CO_2 was slightly less than 200 parts per million by volume (ppm), while during the period from about 10,000 years ago to the early 1700s CO_2 concentrations were relatively stable at ~270ppm.

In the 20th century human activities rapidly altered the composition of the atmosphere in ways that influence Earth's energy balance. Atmospheric concentrations of man-made greenhouse gases like chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), as well as sulfur hexafluoride (SF_6) are all due to industrial development. Several of the important naturally occurring greenhouse gases (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) increased dramatically in the 20th century, especially since ~1950 (Figure 2; IPCC 2007). Carbon-dioxide emissions from burning fossil fuels and converting forests into agricultural lands, account for the observed rise in atmospheric CO_2 concentrations. Increased industrial activity and use of nitrogen fertilizer are key factors contributing to the observed rises in N_2O. In contrast, causes for changing methane concentrations are not well understood, although livestock and certain types of agriculture are known to be large producers of methane. The growth in atmospheric methane concentrations began slowing in the 1980s, and methane concentrations were basically stable from 1999-2002 (Dluglokenky et al., 2003). Based on measurements obtained from deep ice cores from Antarctica, the current CO_2 and CH_4 concentrations are higher now than at any time in (at least) the past 650,000 years.

Figure 2: Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colors for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. Reproduced from the IPCC 2007 Summary for Policymakers.



Key greenhouse gases emitted by human actions have long residence times in the atmosphere (Tab. 1). A molecule of CO_2 can remain in the atmosphere from 5 to 200 years. Synthetic greenhouse gases produced for industry have typical residence times of many centuries to millennia, while methane typically persists for about a decade (Tab. 1).

Table 1: Residence times of greenhouse gases in the atmosphere (after IPCC 1990).

Carbon Dioxide (CO_2)	50-200 years (the range varies with sources and sinks and depends on the equilibration times between atmospheric CO2 and terrestrial and oceanic reserves)
Methane (CH_4)	12 years
Nitrous Oxides (N_2O)	120 years
CFC-11 (a Chlorofluorocarbon)	50 years
HCFC-22 (a Chlorofluorocarbon)	12 years
Perfluorocarbon (CF_4)	50,000 years

Aerosols, small airborne particles that influence the Earth's energy balance, also changed dramatically in the 20th century. Natural sources for aerosols include sulfur dioxide from volcanic eruptions, dust from desert areas, smoke from biomass burning, and salt from sea-spray. In the 20th century anthropogenic sources have contributed a growing portion of atmospheric aerosols; primarily smoke, soot, and sulfuric acid from burning fossil fuels and dust from intensive farming practices. For example, sulfuric acid deposition on Greenland ice rose dramatically with increased emissions from industrial activities in eastern North America from the 1950s until the 1990s. Sulphate deposition decreased in the 1990s as sulphate emissions were reduced to combat acid rain and other regional air quality problems in northeastern North America. Unlike greenhouse gases, aerosols have a short residence time in the atmosphere. This means that aerosols and their impacts on climate tend to be localized around source regions and they are unevenly distributed in space and time.

The net impacts of aerosols on climate are complex and poorly understood. One direct effect of aerosols is to cool the local climate by reflecting incoming solar energy back to space. Increased aerosol concentrations also work to increase the number of water droplets in clouds, leading to smaller cloud droplets that reduce the rate at which water droplets fall out of clouds. A shift to smaller cloud droplets prolongs the lifetime of clouds so that they reflect more sunlight, thereby indirectly cooling local climate, and decreases the likelihood that droplets are large enough to fall to the ground before evaporating, thereby leading to decreased precipitation. Black soot offers yet another complication to aerosol impacts on climate. Black carbon in the atmosphere produced by burning biomass or fossil fuels can absorb sunlight and warm the atmosphere in ways that counter the direct and indirect aerosol cooling produced from increased reflection of sunlight.

Ozone (O_3) is another important trace gas in the atmosphere whose concentrations have changed substantially in the 20th century. The seasonal development of an Antarctic "ozone-hole" was first documented in the mid-1970s, and is now understood to ultimately arise from emissions of man-made industrial gases known as chlorofluorocarbons. Stratospheric ozone is crucial for life at the Earth's surface because it effectively filters out 95 to 99% of the harmful ultraviolet radiation that comes from the sun. Ozone is also an important greenhouse gas. While stratospheric ozone concentrations declined in the 20th century, ozone concentrations near ground level increased in smoggy areas as a consequence of hydrocarbon emissions from burning fossil fuels. This "bad" ozone caused in the formation of smog can damage lung tissue and plants, and serves to locally increase the greenhouse effect in polluted areas. On a global average the net effect of total ozone changes has been to slightly increase the greenhouse effect (see IPCC 2007).

Indicators of Global and Regional Climate Change

Warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level (IPCC 2007). Globally averaged surface air temperature records indicate two periods of strong global-scale warming in the past century, the first taking place from 1910-1945 and the second beginning in the 1970s and continuing to present (Fig. 3). Global average surface temperatures were relatively stable from the late 1800s through 1910, and cooled slightly from 1945 to the mid-1970s. Eleven of the last twelve years (1995 -2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The linear warming trend over the last 50 years (0.13 +/- 0.03°C per decade) is nearly twice that for the last 100 years. The total global average temperature increase from 1850 – 1899 to 2001 – 2005 is 0.76 +/- 0.19°C (IPCC 2007). Urban heat island effects are real but local, and have a negligible influence (less than 0.006°C per decade over land and zero over the oceans) on these values. Analysis of various climate proxies for the Northern Hemisphere suggest that the rate of warming observed in the 20th century, as well as the magnitude of global temperatures from 1990 to 2004, is unprecedented in the past 2000 years (Moberg et al. 2005).

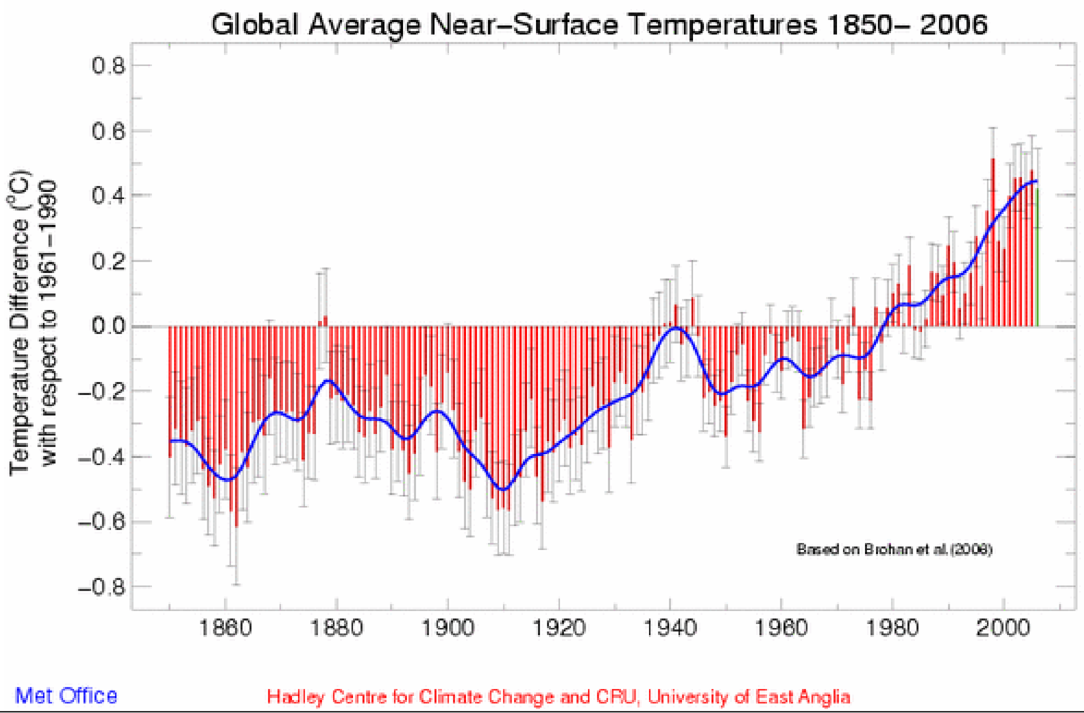


Figure 3: Globally averaged annual mean surface temperatures expressed as deviations from the 1961-90 average. Annual averages are shown with the red bars, a smoothed indication of trend is shown by the heavy blue line. Figure obtained from the Hadley Center's Climate Research Unit web-page: *www.metoffice.com/research/hadleycentre/CR_data/Annual/HadCRUG.gif*

The spatial pattern of 20th century warming was not uniform across the globe. The largest warming trends were in Alaska, western Canada, Russia, and the Antarctic Peninsula, with smaller warming trends over the global oceans and tropical land areas. Twentieth century surface temperatures cooled slightly in parts of the Antarctic, parts of the southern Ocean, and the North Atlantic Ocean just south and east of Greenland (IPCC 2001). The warming trends were also greatest at nighttime, and in the wintertime.

The cryosphere, the part of the Earth's surface that is perennially frozen or below the freezing point, is a crucially important part of the Earth climate system. The most important influences on the cryosphere come from its interactions with the atmosphere, ocean, and land system. Feedbacks between the cryosphere and other components of the climate system can yield especially high regional, and even global, climate sensitivity. For example, *ice-albedo* (surface reflectivity) feedback in polar regions can lead to a high amplification of a small initial warming. Ice is highly reflective, so melting ice increases the amount of sunlight absorbed, which raises surface temperatures, melts more ice, and leads to a positive feedback of the initial warming. Similar sets of feedbacks exist with snow cover and sea ice, such that an initially small amount of melt can start a rapid process of additional melting and surface warming (NRC 1998). Changes in permafrost, snow and ice cover are also ecologically important. Snow and sea ice insulate the surfaces below them from what can be extremely cold atmospheric temperatures. Melting permafrost can alter moisture infiltration rates in ways that lead to large changes in soil moisture and vegetation cover. In summary, the cryosphere directly influences climate through its role in the surface energy balance, and indirectly through its ecological effects on biogeochemical cycles, photosynthesis in terrestrial and marine plants and the decay of organic matter.

The Intergovernmental Panel on Climate Change (IPCC 2007) highlights the following cryosphere indicators of global climate change:

- Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise (ice caps do not include contributions from the Greenland and Antarctic ice sheets).
- New data since the IPCC's Third Assessment Report (IPCC 2001) now show that losses from the ice sheets of Greenland and Antarctica have *very likely* contributed to sea level rise over 1993 to 2003. Flow speed has increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior of the ice sheets. The corresponding increased ice sheet mass loss has often followed thinning, reduction or loss of ice shelves or loss of floating glacier tongues. Such dynamical ice loss is sufficient to explain most of the Antarctic net mass loss and approximately half of the Greenland net mass loss. The remainder of the ice loss from Greenland has occurred because losses due to melting have exceeded accumulation due to snowfall.

There were pronounced regional cryosphere changes in the latter half of the 20th century. Along the Antarctic Peninsula, the Wordie Ice Shelf and the Larsen Ice Shelf disintegrated in recent decades, dramatic indicators of a complex response to very strong regional warming trends of over 2.5°C since the 1950s. The Ward Hunt Ice Shelf, the Arctic's largest ice shelf located on the north coast of Ellesmere Island in Canada's Nunavut territory, fractured in September 2003 and released nearly all the freshwater from what was the Northern Hemisphere's largest ice-shelf lake.

Expected Impacts of Human-Caused Increases in the Natural Greenhouse Effect

For the past few decades the international climate research community has been assessing the possible impacts of an intensified greenhouse effect on Earth's climate. This research has relied on climate models that balance the incoming energy from the sun with the outgoing infrared energy emitted by the Earth. The most sophisticated approaches employ computer simulations for key aspects of the Earth's climate system, including atmospheric winds and pressure patterns, clouds, ocean currents and temperatures, ice and snow cover, and the ecology (photosynthetic plants) and chemistry that controls greenhouse gas concentrations in the atmosphere. At this extreme, the climate problem is a collection of very complicated problems that require the biggest and fastest computers on Earth. Teams of scientists work together to develop, operate, and diagnose the behavior of the most sophisticated computer models. At another extreme are energy-balance models that aim to balance the incoming energy from the sun with the Earth's outgoing infrared energy with very simplified physics. At both the very simple and very sophisticated extremes, every climate model in use today finds that increasing concentrations of greenhouse gases in the 21st century will intensify the greenhouse effect and warm the Earth's surface and lower atmosphere.

Uncertainty about future climate is due to two main factors. First, no one can know the exact quantities of CO_2, methane, and other important greenhouse gases that will be emitted in the next century. Projecting future greenhouse gas emissions requires educated guesses about global economics, technology, and population. The second factor of uncertainty is our limited ability to understand exactly how sensitive the climate system is to a given change in greenhouse gas concentrations. There remain major challenges in simulating the behavior of clouds, the effects of aerosols, the carbon cycle, and how the ocean moves heat from its surface to deeper waters. Clouds, aerosols, the carbon cycle, and the way that oceans transport heat become crucially important for understanding how sensitive climate is to future changes in the greenhouse effect.

The IPCC has coordinated a series of climate model experiments as part of the international effort to assess the future impacts of human-caused climate change. Since 1988, the IPCC has issued major reports on global climate change science, impacts, and policy-responses about every five years (the fourth assessment report completed in 2007). Scientists involved in the IPCC assessments have explored the emissions uncertainties by examining a wide range of possible emissions futures. In order to gauge the uncertainties due to climate sensitivity to a given increase in greenhouse gases, scientists have examined the response of multiple models that have a range of climate sensitivities because they employ slightly different parameters for key physical processes. For the IPCC's Fourth Assessment Report, published in 2007, the end result of their collection of emissions scenarios and model sensitivities suggests a range of ~1.1 to 6.4º C global average warming by 2100, with more warming at higher latitudes and less in the tropics, and more warming over land than over the oceans (IPCC 2007*)*.

At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones. Table SPM-2 (IPCC 2007) also provides a good summary of recent trends, assessment of human influence on the trend, and projections for extreme weather events for which there is an observed late 20th century trend. Key conclusions of the IPCC's Fourth (IPCC 2007) and Third (IPCC 2001) Assessment Reports include:

- Since the IPCC's first report in 1990, assessed projections have suggested global averaged temperature increases between about 0.15 and 0.3°C per decade for 1990 to

2005. This can now be compared with observed values of about 0.2°C per decade, strengthening confidence in near-term projections.

- Model experiments show that even if all radiative forcing agents are held constant at year 2000 levels, a further warming trend would occur in the next two decades at a rate of about 0.1°C per decade, due mainly to the slow response of the oceans. About twice as much warming (0.2°C per decade) would be expected if emissions are within the range of the emissions scenarios considered. Best-estimate projections from models indicate that decadal-average warming over each inhabited continent by 2030 is insensitive to the choice among emissions scenarios and is very likely to be at least twice as large as the corresponding model-estimated natural variability during the 20th century.
- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.
- Advances in climate change modeling now enable best estimates and likely assessed uncertainty ranges to be given for projected warming for different emission scenarios.
- Best estimates and likely ranges for globally average surface air warming for six emissions marker scenarios are provided by IPCC (2007). The best estimate for the low emissions scenario (B1) is 1.8°C (likely range is 1.1°C to 2.9°C), and the best estimate for the high emissions scenario (A1FI) is 4.0°C (likely range is 2.4°C to 6.4°C) by the end of the century. Although these projections are broadly consistent with the span quoted in the IPCC's Third Assessment Report (1.4 to 5.8°C), they are not directly comparable. The Fourth Assessment Report is more advanced as it provides best estimates and an assessed likelihood range for each of the marker scenarios. The new assessment of the likely ranges now relies on a larger number of climate models of increasing complexity and realism, as well as new information regarding the nature of feedbacks from the carbon cycle and constraints on climate response from observations.
- Warming tends to reduce land and ocean uptake of atmospheric carbon dioxide, increasing the fraction of anthropogenic emissions that remains in the atmosphere. For the A2 emissions scenario, for example, the climate-carbon cycle feedback increases the corresponding global average warming at 2100 by more than 1°C. Assessed upper ranges for temperature projections are larger than in the IPCC's Third Assessment Report mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks.
- Fourth Assessment Report model-based projections of global average sea level rise at the end of the 21st century (2090-2099) have a narrower range than in the Third Assessment Report mainly because of improved information about some uncertainties in the projected contributions.
- Models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993-2003, but these

flow rates could increase or decrease in the future. For example, if this contribution were to grow linearly with global average temperature change, the upper ranges of sea level rise for IPCC emissions scenarios would increase by 0.1 m to 0.2 m. Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.

- Increasing atmospheric carbon dioxide concentrations leads to increasing acidification of the ocean. Projections based on IPCC emissions scenarios give reductions in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century, adding to the present decrease of 0.1 units since pre-industrial times.
- There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation, and some aspects of extremes and of ice.
- Projected warming in the 21st century shows scenario-independent geographical patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean.
- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions.
- Sea ice is projected to shrink in both the Arctic and Antarctic under all IPCC emissions scenarios. In some projections, Arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.
- Extra-tropical storm tracks are projected to move towards the poles, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century.
- Since the IPCC Third Assessment Report there is an improving understanding of projected patterns of precipitation. Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions, continuing observed patterns in recent trends.
- Based on current model simulations, it is very likely that the slow but important, heat transporting, north to south overturning circulation (also known as the meridional overturning circulation (MOC) in climate research jargon) of the Atlantic Ocean will slow down during the 21st century. The multi-model average reduction by 2100 is 25% (range from zero to about 50%) for emission scenario A1B (assumes a balanced mix of future energy sources with increased efficiencies due to technology improvements; no single source of energy is overly dominant (IPCC 2001)). Temperatures in the Atlantic region are projected to increase despite such changes due to the much larger warming associated with projected increases of greenhouse gases. It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence.

- Both past and future anthropogenic carbon dioxide emissions will continue to contribute to warming and sea level rise for more than a millennium, due to the timescales required for removal of this gas from the atmosphere.
- Based on global model simulations and for a wide range of scenarios, global average water vapor concentration and precipitation are projected to increase during the 21st century. By the second half of the 21st century, it is likely that precipitation will have increased over northern mid- to high latitudes in winter.
- The frequency of heavy precipitation events will very likely increase over most land areas, which is consistent with atmospheric warming and observed increases in atmospheric water vapor.
- It is very likely that there will be warmer and more frequent hot days and nights over most land areas.
- It is very likely that the frequency of warm spells and heat waves will increase over most land areas.
- It is likely that the area affected by drought will increase.
- It is very like that there will be higher minimum temperatures, fewer cold days and nights over nearly all land areas.
- Confidence in projections of changes in the future frequency, amplitude, and spatial pattern of El Niño events in the tropical Pacific is tempered by some shortcomings in how well El Niño is simulated in complex models. Current projections show little change or a small increase in amplitude for El Niño events over the next 100 years.

Expected Regional Impacts of Global Warming in the Pacific Northwest

Climate records show that the Northwest (regionally averaged) has warmed about 1.0 ºC since 1900, or about 50% more than the global average warming over the same period (Mote 2003a). Most glaciers in the region reached their recent maximum extent in the mid-1800s and since that time have been in rapid retreat. Recent studies indicate that the retreat of the past ~150 years has now brought many Northwest glaciers back to levels last seen ~6,000 years ago, a time near the end of a prolonged warm and dry period that is indicated by ancient pollen records and moraines (Walker and Pellatt, 2003). Regularly collected measurements indicate that Northwest springtime snow pack from the western Rockies to the coast, and from the central Sierras in California to southern British Columbia, declined substantially between 1950 and 1997 in part due to a reduction in precipitation and in part due to rising winter temperatures during this period (Mote et al. 2003b; 2005b).

These measurements indicate that for many individual recording sites decreases in this period were up to 60% in April 1st snow pack for the "warmest" locations in the Northwest -- areas including the lower elevations of the Cascades and the Olympic mountains in Washington. Over the period from 1948 to 2000 the timing of springtime snow melt runoff came earlier in the vast majority of rivers in the Northwest, with advances in peak runoff timing of one to a few weeks depending on the basin (Stewart et al. 2005). Increases in regional winter and spring surface temperatures account for much of the documented runoff timing trend for western rivers.

Taken together, a wealth of evidence paints a very consistent picture of a warming climate over the past 150 years for both the Pacific Northwest and the Earth as a whole. However, at the regional scale of the Pacific Northwest, substantial interannual and interdecadal variability in climate is caused by large-scale patterns of natural climate variability. Specifically, regional climate variations associated with the tropical El Niño Southern Oscillation (ENSO) and the extratropical Pacific Decadal Oscillation (PDO) had strong influences on Pacific Northwest climate in the past century, and PDO variability contributed substantially to Pacific Northwest precipitation and temperature trends in the 2nd half of the 20th century (Mantua et al. 1997; Mote et al. 2003a; Mote 2006).

Salathé et al. (in press) recently collected the output from 20 different global climate model simulations that were run as part of the IPCC's Fourth Assessment Report. The relevant precipitation and surface temperature fields for the Pacific Northwest region (here defined as the region between 124˚ and 111˚ west longitude, 42˚ and 49˚ north latitude, encompassing Washington, Oregon, Idaho, and western Montana) were extracted in order to generate a regional average time series. They examined output from 10 different models using, each using 2 different greenhouse gas and aerosol emissions scenarios, A2 and B1, which lie near the upper and lower limits of the full range of IPCC emissions scenarios considered in the IPCC's latest assessment activities. The combination of 10 models each run under 2 different emissions scenarios provides a total of 20 different future climate scenarios. Based on an assessment of each model's response to a specified change in greenhouse gas and aerosol concentrations, they note that the models used in their analysis are neither the most nor the least sensitive on the global scale.

Salathé et al's analysis shows the projected warming rate for the next century to be in the range of 0.1-0.6˚ C/decade, with a 20-scenario average of 0.3˚ C/decade (Fig. 4). For comparison, the observed rate of warming in the 20th century was ~0.1˚C/decade. Because of long residence times for greenhouse gases and substantial inertia in energy systems (and emissions) there is relatively little spread between the high and low model estimates for regional warming over the next few decades. There is much greater spread between the high-end and low-end model estimates for regional (and global) warming by the 2nd half of the 21st century as future warming increasingly depends on future emissions.

Projected precipitation changes are relatively modest and unlikely to be distinguishable from natural variability until late in the 21st century (Tab. 2). Most models project long-term trends with increases in winter precipitation and decreases in summer precipitation for the Pacific Northwest region. Notably, most models also generate substantial year-to-year and decade-to-decade fluctuations in regional precipitation that is comparable to observed precipitation fluctuations in the 20th century. A summary of the range of model projections for temperature and precipitation for the 2020s, 2040s, and 2080s is provided in Table 2.

Table 2: Summary of the range of 20 future climate scenarios for the Pacific Northwest examined by Salathé et al (in press). Note that "2020s" means the 2010-2040 average minus the 1970-2000 average, similarly for the 2040s and 2080s. Thirty year averaging periods were chosen to help distinguish each model's anthropogenic climate change signal from its internal decadal variations.

2020s	temperature	Precipitation
Low	0.4˚ C	-4%
Average	1.1˚ C	+2%
High	1.8˚ C	+6%

2040s	temperature	Precipitation
Low	0.8˚ C	-4%
Average	1.6˚ C	+2%
High	2.6˚ C	+9%

2080s	temperature	Precipitation
Low	1.6˚ C	-2%
Average	3.1˚ C	+6%
High	4.9˚ C	+18%

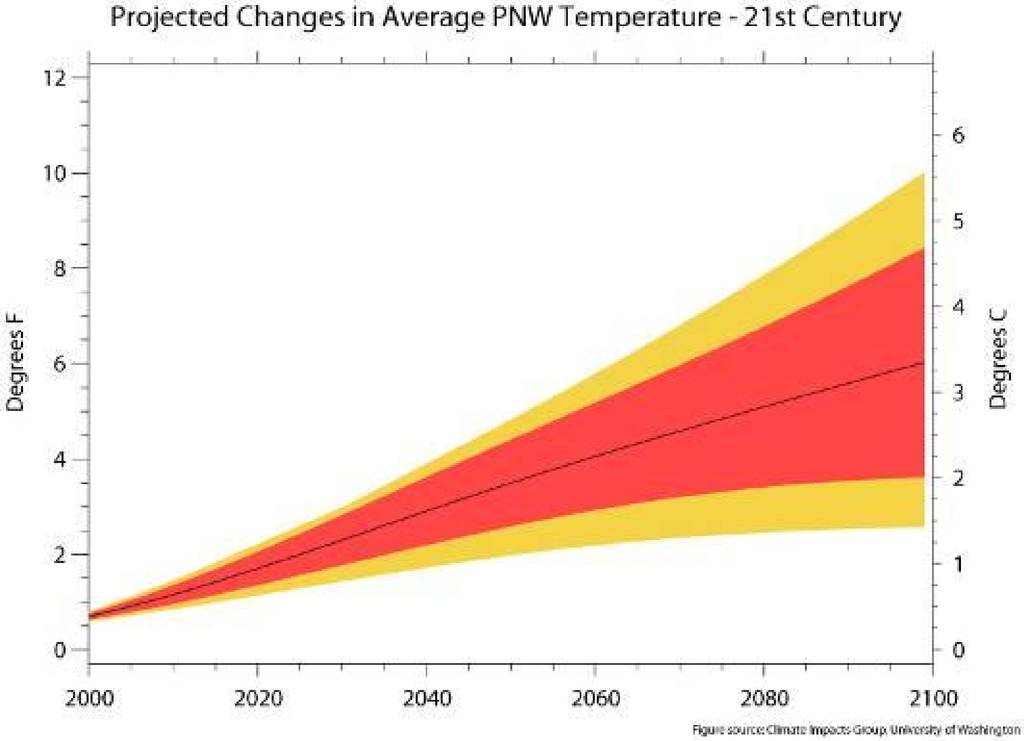


Figure 4: Projected changes in Pacific Northwest average annual temperature for the 21st century. This figure shows the range of warming projected for the Pacific Northwest from 20 simulations of future climate by global climate models. The average of the 20 simulations is shown by the black line. The red shading encloses about 70% of the model results while the gold shading shows the lowest and highest values. *Figure source: Climate Impacts Group, University of Washington.*

Impacts on Snow Pack, Stream Flow and Water Temperature

Quantitative assessments of the impacts of climate change on hydrology and water resources have been reported by researchers to link the output from global climate models used by the IPCC to physically-based hydrologic models for the Columbia River Basin (e.g. Hamlet and Lettenmaier 1999; Payne et al. 2004; Hamlet 2006). These and related studies have consistently identified the following types of climate change impacts on the snow pack, stream flow, and water quality in the Columbia Basin:

- **Warmer temperatures will result in more precipitation falling as rain rather than snow**

The expectation that warmer air temperatures will result in a shift to more winter/spring rain and runoff, rather than snow that is stored until the spring/summer melt produces runoff, is among the most confident projections for global warming impacts on Pacific Northwest hydrology. It is important to note that the sensitivity to a given temperature change depends on how near or far each location's mean winter temperature is to freezing. For locations at high elevations in the interior Columbia Basin, winter temperatures are typically far below freezing in winter, so one to a few degrees C of warming may not initiate a shift from snow to rain. In contrast, low elevation temperature in the Columbia Basin are typically much closer to freezing, so a small amount of warming in winter can cause these "transient snow zone" locations to experience substantial shifts in accumulated rainfall versus snowfall in winter (Fig. 5).

- **Snow pack will diminish, and the timing of stream flow will be altered**

For watersheds that historically develop a seasonal snow pack, warming air temperature in winter and spring will lead to more precipitation falling as rain rather than snow (see lower panels of Figure below). For affected watersheds, the reduction in the amount of water stored in snow pack will result in earlier exhaustion of the snow pack and lower flows in streams from June through September. The Pacific Northwest region's typically low late-summer and early-fall stream flows are likely to be further reduced, while stream flows are likely to rise from December through April. Different watersheds will have different sensitivities to warming impacts on snowmelt hydrology. For example, a range of climate change impacts scenarios for natural runoff in the mainstem Columbia River at Grand Coulee and The Dalles for the 2040s shows only subtle changes in the shape of the monthly mean hydrograph for those locations, while the same climate change scenarios cause substantial losses of snow and snowmelt runoff for the Spokane and Yakima Rivers (see below). Analysis of historical and simulated snow pack records for the 20th century indicates that mid-elevation watersheds in the Pacific Northwest have demonstrated a high snow pack and runoff timing sensitivity to past fluctuations and trends in winter/spring temperatures (Mote et al. 2003 c; 2005b). These same watersheds will have the highest snow pack and runoff sensitivity to future temperature changes in the next few decades.

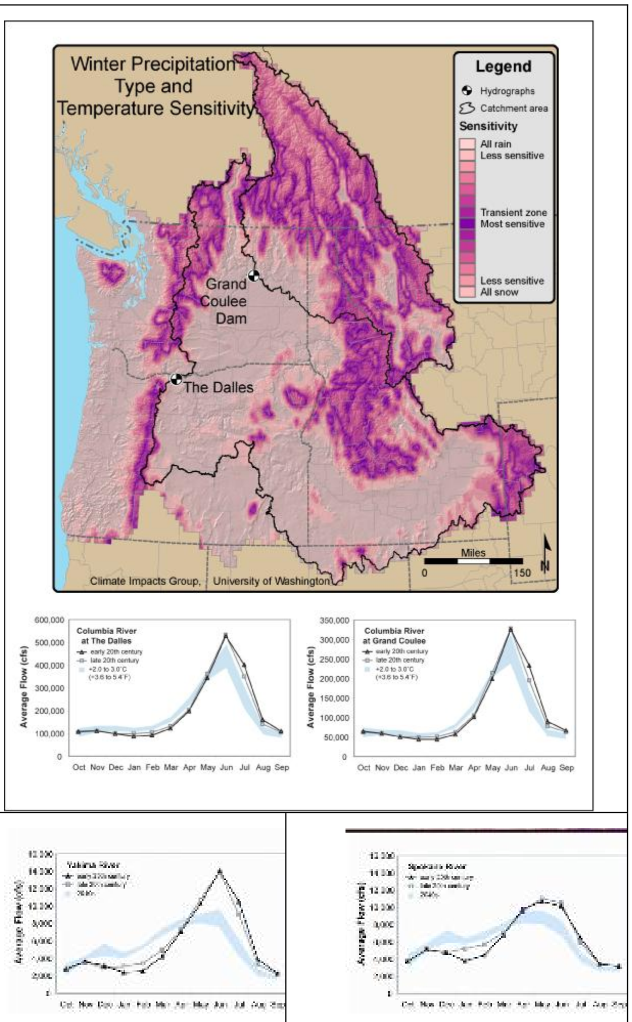
- **Peak river flows will likely increase**

Because the intensity of precipitation events is expected to increase along with rising freezing levels, wet-season runoff and peak flows along many of the region's rivers and large streams is expected to increase (Hamlet 2006).

- **Water temperatures will continue to rise**

Given the close correspondence between surface air temperature and surface water temperature for many streams, the latter is also projected to increase in many Pacific Northwest rivers, streams, and estuaries. The amount of warming will depend on the hydrologic characteristics of each water body. For instance, streams with the least groundwater inflows will warm more than those having the most groundwater inflows.

Figure 5: (upper panel) Winter precipitation sensitivity to warming and (lower panels) projected streamflow changes in the mainstem Columbia River at the Dalles and Grand Coulee, and for the Yakima and Spokane Rivers for a range of 2040s climate change scenarios (annual average temperature changes of +0.8 to +2.6C, annual precipitation changes of -4% to +9%). The hydrographs below the maps show simulated monthly naturalized streamflow. The black line represents simulated natural streamflow for typical hydrologic conditions under early 20th century temperature; the gray line represents simulated natural streamflow for typical hydrologic conditions but late 20th century temperature; the blue swath represents the range of projected streamflow for the 2040s. Reproduced from Casola et al. (2005).



Changes in Terrestrial Ecosystems

What determines the response of terrestrial ecosystems to climate change?

The detailed responses to climate change of biological communities, such as sagebrush steppe or forest, and the wildlife they support, are uncertain because many causal factors are involved and much information on specific causal relationships is missing or imperfect. More research would improve prediction of change in biotic communities with climate change, but considerable uncertainty will remain. The predictions of biological communities under unprecedented climatic and landscape conditions, and under unprecedented rates of change in these conditions, must include uncertainty. The species composition and health of ecosystems is influenced not only by climate but also by interactions among species within communities, including interactions with non-native species that are new players in those communities and changes in interactions within a community as some species become locally extirpated or extinct and different sets of species are present. Additionally, landscape pattern and many ecosystem processes will be altered as climate, species, and human population and land use simultaneously change (e.g., Aber et al. 2001, Schmitz et al. 2003). Thus, although we can describe the ongoing and expected changes in climate and predict direct responses of some species to them, and we can define the factors that will be important in determining ecological responses and outcomes, considerable uncertainty of the final resulting communities will remain.

The response of species to global climate change is mediated by several factors:

Physiological suitability and migration rates

Species have areas of occurrence (ranges) that are limited by suitable climatic conditions, especially temperature and moisture availability. Thus, as temperature and precipitation patterns change, species will disappear from parts of their former ranges that have become unsuitable for their existence, and they may appear in new areas where they were formerly absent. Whether or not the ranges move or expand depends on the ability of organisms to disperse or migrate to the areas that become suitable. Paleoecological data have been used to infer the rates at which populations migrated across the landscape in the past, changing range as climate changed and so persisting (e.g., Graham and Grimm 1990, Jackson and Overpeck 2000). Migration rates for tree taxa during the Holocene were roughly 1000 m/yr (Pitelka and PMWG 1997).

Recently, shifts have been observed in the ranges of many species that are in directions predicted by climate change projections and that are correlated with changes in climate (Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2005, Parmesan 2006). These changes include poleward and elevationally upward movements of many insects, birds, trees, and forbs. It is expected that the ranges of species that are able to migrate rapidly enough to track climate changes will shift to new, suitable areas as climate changes. However, fragmentation of suitable areas may be a significant problem for some species. In Western North American, the area of future habitat that is suitable climatically for species is often small and disjunct, reflecting the heterogeneity of the Western landscape. Land use will reduce the available habitat that is both suitable climatically and available to plants and wildlife and will impede the ability of species to successfully disperse and shift ranges as climate changes. Western North America supports high habitat diversity, but the spatial extent of any habitat type may be relatively small, and patches may be separated from similar habitat by large distances. The relative isolation of habitat patches means natural dispersal may be a significant barrier to plants and wildlife adjusting to climate change through range shifts.

Biotic interactions within communities

In addition to requiring suitable physical conditions of temperature and water to thrive, all species also are influenced by many ecological interactions including disease, predation, competition, and food resources. Because the magnitude of species' range shifts is expected to be large, there will no doubt be changes in competitive interactions of species, which could affect the viability of some. Predicting future competitive interactions is especially difficult. Paleoecological evidence shows that species respond individualistically to climate change (Graham and Grimm 1990, Webb 1995, Jackson and Overpeck 2000), which means that the mix of species that interact in a location has changed with changing climate in the past and must be expected to continue to do so as climate changes in the future. Climate change also could eliminate an important predator and allow a species to expand its range. The interaction with humans due to our impacts on land use will no doubt be an especially important species interaction (Dale 1997).

Additionally, the Columbia River Basin has many non-natives species, some invasive, and the interactions of these species with existing and shifting biological communities are only beginning to be understood. One example is cheatgrass (*Bromus tectorum*), which is invasive through much of the sagebrush steppe region and is a leading factor in degradation and conversion of the remaining shrubland habitat (Knick et al. 2003).

Biotic interactions are often dependent on phenology, and directional changes in phenology (the seasonal timing of activities of organisms, such as bud break, spawning, birth, hibernation, emergence, migration, etc.), that are correlated with directional changes in climate have been observed worldwide in recent decades (e.g., Inouye et al. 2000, Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2005, Parmesan 2006, Stenseth and Mysterud 2005). These changes include earlier arrival of migrant bird species, earlier emergence of hibernating animals, and earlier bud break and flowering of some plants. These changes provide evidence of the developing biological responses to climate change, and they also establish a set of previously unanticipated biological hazards of global climate change: mismatch or formerly coordinated phenology of plants and animals. Examples include migration timing that no longer corresponds well with the timing of growth of plants or animals that provide the food for the migrants (Stenseth and Mysterud 2002). An example is the case of the American robin, which was found to arrive at a high-elevation site in Colorado 14 days earlier on average than they did in 1981 and for which the interval between arrival time and time at which bare ground was first observed had grown by 18 days (Inouye et al. 2000). This dilemma appears to result from differences in the rate of climate change at lower elevations, from which the robins migrate and where winter temperatures are warmer and snowmelt has advanced significantly, and that at higher elevations, where the combination of winter warming with higher snow pack has prevented an earlier spring.

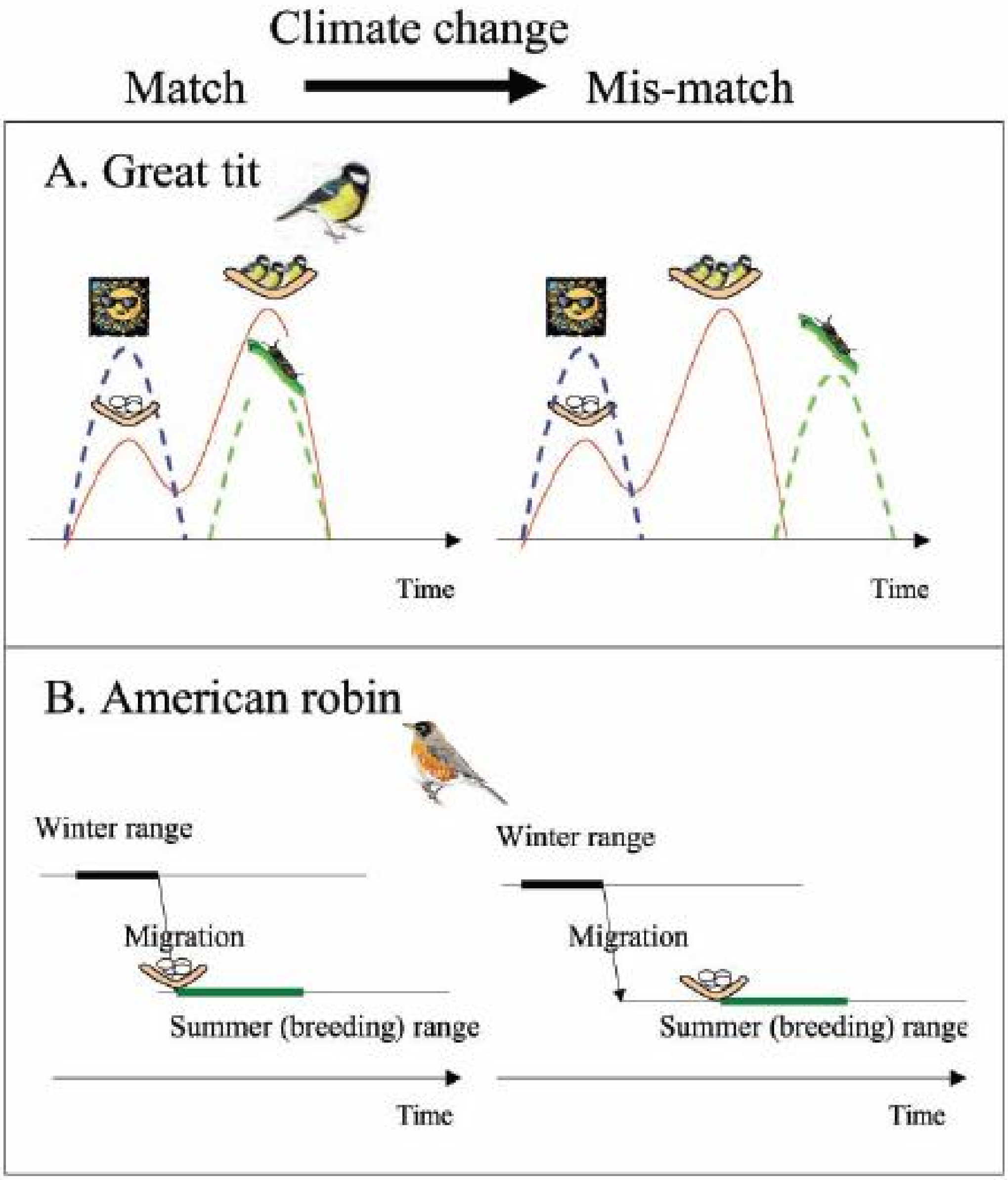


Figure 6: A central concept when studying the relationship between climate, phenology and other life history traits is the match vs. mismatch of the climate-phenology response within different components of the ecological system. (A) The environmental cues triggering the onset of egg laying change in asynchrony to the environmental conditions prevailing when chicks are reared and when birds' energetic demands are highest as shown for Great tit. (B) The differential climate change between summer and winter ranges may lead to problems in the transition for migratory birds, such as the American robin. (Figure from Stenseth and Mysterud 2002).

Because organisms cue on factors that are good indicators of past phenological relationships, but need not cue on the limiting factors themselves, changing temperature patterns may often lead to phenology mismatches between interdependent species with different cuing patterns and different climatic dependencies. Researchers and field biologists have voiced strong concerns that changing patterns of phenology and resulting phenology mismatches will result in breeding failures due to pollination failure, lack of appropriate food sources, and weather extremes such as early frosts, late freezes, or unseasonal snowfalls.

There are a number of reasons for concern that interactions involving natural enemies such as forest or rangeland pests will have increasingly strong effects as climate changes. It is well established that the life cycles and population dynamics of insects are highly responsive to patterns of temperature and moisture (Logan et al. 2003, Logan 2006, Williams and Leibhold 2002), and drought has been linked to many cases of insect outbreaks in both rangelands and forests (Barbosa and Schultz 1997). As climate changes and new areas become more and less suitable for particular species, the climatic overlaps of pest and host species will re-assort. Ranges of insects will change more rapidly than those of perennial host plants, and host plants at the edges of formerly suitable areas of their ranges will become more physiologically stressed. All of these changes are expected to raise the likelihood and intensity of outbreaks of insect pests.

Insects can respond to patterns of climate change more rapidly than most plants. For instance, forest pest insects typically can respond to climate in a year, as opposed to their forest hosts, for which range changes would take decades or longer (Logan 2006). In agreement with this understanding, outbreaks of forest insects are occurring at unprecedented levels in western North America. Bark beetles are a striking example. Mountain pine beetles in the Sawtooth National Recreation Area, home to the headwaters of the Salmon River, which has historically been too cold for outbreaks, have been restricted to small thermally favorable areas, such as the west-facing side of a valley (Logan 2006). Beginning in the mid 1990s, these small localized populations began to increase and merge, forming an outbreak from 1995—2003. Similarly, an outbreak of mountain pine beetle in British Columbia, Canada, is both far north of observed outbreaks and unprecedented in size (10 million ha affected by summer 2005) (Carroll et al. 2003). Outbreak-caused loss of much of the tree cover from many watersheds in interior British Columbia has led to increasing concerns about the impact on hydrology and salmon habitat (Uunila et al. 2006).

In the sagebrush and juniper habitat of the Columbia River Basin, similar problems of increasing insect outbreak are predicted. The most prominent outbreaking insects in these habitats are grasshoppers and Mormon crickets, but other important insects include several species of Lepidoptera (moths), Coleoptera (beetles) and Hemiptera (bugs) (Bentz et al. 2006, Welch 2005). An example is the sagebrush defoliator, *Aroga websteri*, a Lepidopteran, which occasionally defoliates sagebrush over huge areas. Outbreaks of *Aroga* appear to have become larger and more frequent in recent, warmer years. In both forest and rangeland cases, warming temperatures can positively affect the insects directly, and moisture or other climatic stress can increase the susceptibility of plants to insects.

Evolutionary responses

It is also important to consider the nature and extent of evolutionary change in response to changing climate. The fact that rates of change in temperature are large compared with those observed or otherwise documented in the past means that our ability to anticipate evolutionary responses is limited. However, there is evidence already of adaptive genetic change in some species resulting from changing climate. Species for which such evolutionary change is documented include mosquitoes, fruit flies, birds, and squirrels, all of which have populations for which long-term studies have established adaptive changes in phenology that correspond to changes in seasonal weather patterns such as earlier spring, longer growing season, and shifts in the time that is favorable for reproduction (Bradshaw and Holzapfel 2006). In the smallest of these species, mosquitoes, which have the shortest generation times, clear adaptive evolutionary change was seen over as little as 5 years, whereas for the larger and longer-lived squirrels and birds, changes were smaller and were apparent only over longer time periods, 10 years in red squirrels and more than 30 years in great tits. The great tits, despite adaptive changes in phenology, also had declining reproductive success, so it is unclear whether the rate of evolution in the population will be sufficient to track changing seasonal patterns of food or if the population will become locally or more broadly extinct. The relative rates of environmental change and evolutionary adaptation will surely vary greatly among populations, but it appears that rates of climate change may outstrip the rates of adaptive change for many longer-lived species.

The Predicted Patterns of Change in Terrestrial Ecosystems of the Columbia River Basin

Ecosystem Processes and Disturbance: Fire and Outbreaks of Natural Enemies

Fire is correlated strongly with climate, and virtually all future climate scenarios predict increases in fire in western North America, including the Columbia Basin. These predicted increases would extend the changes in fire frequency and intensity that characterize recent records. Wild-fires have been more frequent, larger, and more intense in the past 50, and especially the past 15, years in the shrub steppe and forested regions of the West. Westerling et al. (2006) found longer wildfire seasons and higher frequency and duration of wildfires in records of fires in western US forests since 1970. The largest increases were in the mid-elevation Northern Rockies and were strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

Fires frequency, intensity, and the duration of fire season have increased in past decades in intermountain forest and sagebrush steppe (Fig. 7). These changes were associated with temperature trends (McKenzie et al. 2004, Westerling et al. 2006). Generally, warmer and earlier springs correspond to years of higher fire hazards (Westerling et al. 2006).

Insect outbreaks are an even more significant source of mortality and disturbance in North American forests than is fire (Dale et al. 2001, Logan et al. 2003). Outbreaks of forest insects affect roughly 45 times as much area as does fire (Dale et al. 2001), and forest insects and pathogens are especially likely to change with climate. Insects are typically more mobile than their forest plant hosts, and they have more rapid growth rates and life cycles that will be more quickly responsive to climate warming. In recent years, hot, dry weather has led to an increase in forest insect outbreaks, and it is expected that continued global warming will increase this trend, with insect outbreaks becoming more common and more widespread and with the ranges of insect pests shifting and in many cases expanding to invade new areas and new forest types (Logan et al. 2003).

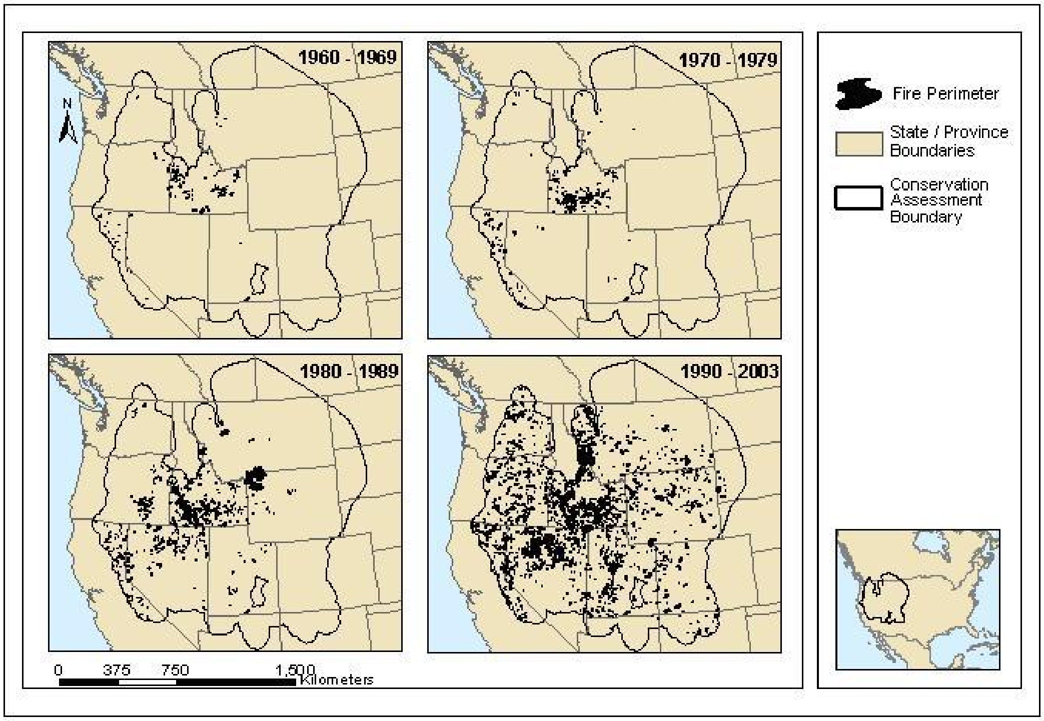


Figure 7. Increase in fire frequency in the Western United States, including interior regions of the Columbia River Basin. From Connelly et al. 2004 (Figure 7.6), as given at http://sagemap.wr.usgs.gov/FTP/images/fig7.6.jpg.

Water Resources

Hydrology is strongly linked to climate, and changes in climate are expected to alter hydrology and so affect availability of water to plants, fish and wildlife, and people.

Both changes in mean climate and changes in variability, especially size and frequency of extreme events, are of significance. Hurd et al. (1999) identified indicators of the vulnerability of water resources in the United States, grouped them to those that affected primarily (1) water supply, distribution, and consumptive uses or (2) stream use, water quality, and ecosystem support, and classified each into low, medium, and high vulnerability classes relative to all the 204 four-digit HUC watersheds of the continental United States. They then analyzed the vulnerability to climate change of the indicators separately and for the two aggregate categories. The watersheds most vulnerable to level of development, natural variability, and dryness ratio were clustered in the West (Hurd et al. 1999), and most of the interior Columbia Basin was characterized as moderately or highly vulnerable in these areas, given climate change. The Snake River Plain and southeast Oregon were also highly or moderately vulnerable to ground water depletion. The aggregate index of vulnerability to water supply, distribution, and consumptive use identified most of eastern Washington and Oregon and southern Idaho as at moderate vulnerability.

The interior West was found to be of low vulnerability to flood risk in comparison with much of the more heavily-populated United States, but that was primarily because of lower population densities in the interior West. The risk would likely be evaluated as regionally high and would be expected to increase substantially with increasing population and development. The paper also found that the cold-water fisheries of the Rocky Mountain Regions were among the most vulnerable to impacts of warmer temperatures, with northern and eastern Idaho highly vulnerable, and most of the Oregon and Washington parts of the basin moderately vulnerable. The study concluded that the vulnerability of western watersheds that are currently water stressed by competing and rising water demands, which are likely to continue to rise, are of particular concern.

Vegetation/Wildlife Habitat

In the western United States, steep environmental gradients (for instance, in topography, elevation, and water availability) mean that there will be relatively few areas where a species' potential range does not shift significantly under future climate scenarios (Shafer et al. 2001). The steep environmental gradients also mean that movement corridors, which would facilitate the migration of plants and animals to more suitable areas as climate changes, may be limited and should be given particular consideration in planning to mitigate for climate change. Many assessments of likely ecological responses to climate change conclude that several community types that are significant in the Columbia River Basin are likely to decrease greatly in area or disappear from the region. These include alpine habitats, subalpine spruce-fir forests, aspen stands, and sagebrush steppe (Hansen et al. 2001, Shafer et al. 2001).

Many studies have combined simulations of future climates with information on the climate tolerances of plant species to examine the likely occurrence and range limits of important plant species that define Columbia Basin habitat types, such as sagebrush (*Artemisia tridentata*), the species that characterizes shrub-steppe vegetation of the intermountain West, aspen (*Populus tremuloides*.), and important forest tree species such as subalpine fir (*Abies lasiocarpa)* and Douglas fir (*Pseudotsuga menziesii)*. We review the most common predictions for major species of Columbia River Basin habitats below.

Riparian areas and wetlands

Riparian areas and wetlands are habitats where terrestrial and aquatic ecosystems are most closely linked. They are among the most diverse and dynamic habitats on the Earth, and are especially important sources of diversity in arid areas such as the interior Columbia River Basin (Naiman et al. 1993, Wissmar 2004). These habitats are critical to a broad range of wildlife. For instance, over 70% of the vertebrate species in some regions have been reported to use riparian corridors in a significant way during their life cycle (Raedeke 1989 in Naiman et al 1993). In many areas, riparian and wetland habitats have been altered by increasing fire frequency and intensity associated with changing climate and by management actions following fires. The expected continuing increase in fire frequency in the Columbia Basin means that direct impacts of fire on the riparian zone may increase. Additionally, increasing fire frequency and intensity in forests increases the likelihood of habitat damage, with both direct effects of more extensive and intense fire and indirect effects due to post-fire management practices potentially of concern (Beschta et al. 2004, Wissmar 2004).

The expected effects of climate change on riparian areas and wetlands are exacerbated by simultaneous changes in land use and human population. In the West overall, and in the Columbia River Basin, human population, land development, and private land ownership are concentrated disproportionately along waterways, thus introducing sources of conflict between human population and natural resources and biodiversity (Gude et al. 2006, Hansen et al. 2000, Hansen et al. 2002, Smith and Wachob 2006). The diversity of riparian vegetation is thought to be due to the high dynamism of the habitat, including intensity and frequency of floods, variation in soils and topography from natural river channel migrations, and disturbance originating from uplands. Decreased flow variation has resulted in failure of some dominant riparian tree species to establish, causing decrease in the diversity and productivity of the riparian corridor. Past influences of people, such as diking, damming, and irrigation, have in large part simplified riverine and riparian ecosystems (Naiman et al. 1993, Poff et al. 2007) and eliminated many wetland habitats (Sherwood et al. 1990), which would be expected to reduce the diversity of species dependent on these habitats. Climate change is likely to work in concert with these other factors to further compromise riparian habitats.

Forests

The Pacific Northwest hosts a complex suite of forests, including coastal temperate (dominated by Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and Douglas fir (*Psuedotsuga menziesii*)), coastal subalpine (with mountain hemlock (*Tsuga mertensiana*) and Pacific silver fir (*Abies amabilis*)), interior montane (with western white pine (*Pinus monticola*) western red cedar, and western hemlock), interior subalpine (with Engelmann spruce (*Picea engelmannii*), subalpine fir, and lodgepole pine (*Pinus contorta*)), and mixed mesic conifer (Ponderosa pine (*Pinus ponderosa*), Douglas fir, and western hemlock) forests (Noss et al. 2006). Predicted climate shifts over the next century, combined with known climate tolerances of the dominant species of these forests, lead to the expectation that there will be dramatic changes in the character of Pacific Northwest forestland (Fig. 8; Shafer et al. 2001, Hansen et al. 2001). Potential habitat for the subalpine species Engelmann spruce and mountain hemlock is expected to contract substantially in the western United States. In fact, alpine habitats, subalpine spruce-fir forests, and aspen are expected to be largely eliminated from the Western United States and displaced northward to Canada. The future distributions of some species, such as Douglas fir, are predicted to be considerably smaller in the region and also include areas significantly removed from the current distribution, which may pose problems for migration and range adjustments. In some areas, forest may expand, occupying sites currently supporting rangeland, as trees are increasingly favored by altered precipitation, enhanced water-use efficiency at elevated CO_2 levels, and a lengthening of the growing season (Millar et al. 2006).

In addition to the predicted shifts of many species' ranges northward with warming temperature, and the expected fragmentation of ranges of many species in the heterogeneous western topography, a number of species are predicted to shift in range from west of to east of the Cascades. Douglas fir, Pacific yew (*Taxus brevifolia*) and red alder (*Alnus rubra*) fall into this category. The potential habitats of dominant rainforest conifers (e.g., western hemlock, western red cedar) are expected to decrease west of the Cascades but expand into mountain ranges of the interior West. In contrast, Ponderosa pine, which is tolerant of relative warm and dry climate, is predicted to expand its range significantly and to occur west of the Cascades.

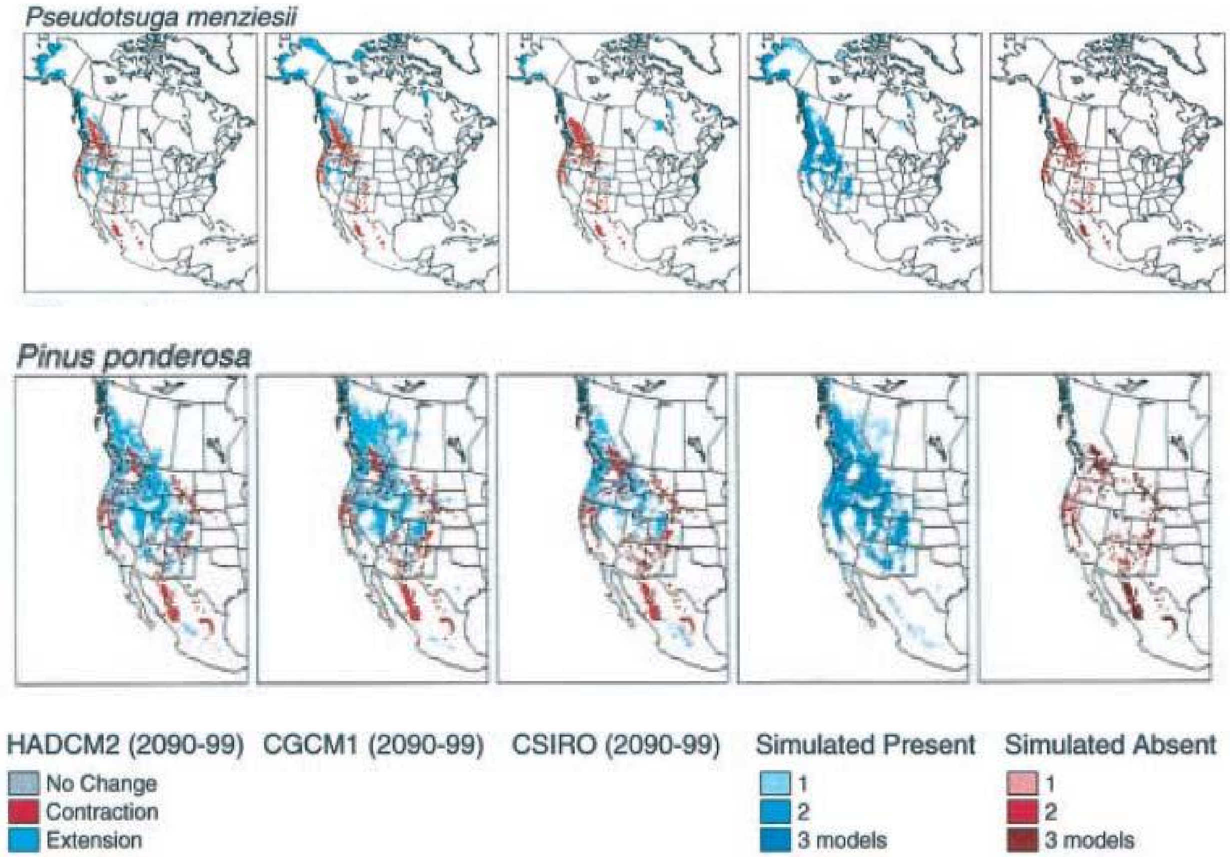


Figure 8. Comparison of observed distributions with future simulated distributions for Douglas fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*) using climate scenarios for 2090-2099 generated by HADCM2, CGCM1, and CSIRO CGM (left three columns). "No change" indicates where the species is observed now and is simulated to occur under future climate conditions; "contraction" indicates where the species is observed at present but is simulated to be absent under future climate conditions; "extension" indicates where the species is not observed now but is simulated to be present under future climatic conditions. Agreement among the future distributions of each species as simulated by the 3 GCM scenarios is displayed as the number of model scenarios under which a species is predicted to be present or absent (right 2 columns). (Figure modified from Shafer et al. 2001).

The increase in mean temperature of the coldest month (MTCO) along the Pacific Northwest coast drives the shift of potential ranges of species from west to east. Many Pacific Northwest tree species have a winter chilling requirement. Douglas fir, one of the major trees of Pacific Northwest forests, has a relatively long chilling period. Increase in MTCO thus means that a large disturbance, such as a stand-replacing fire, could be followed by low seedling establishment and major changes in species composition of

Douglas fir dominated forests. The absence of below-freezing temperature also could allow competitors currently excluded by low temperatures to establish in the region. In the west, the shift from below-freezing to above-freezing mean monthly temperature occurs for a region of the interior West that stretches from northern Arizona to southern Washington.

These projected changes in suitable ranges of species are only initial predictions of where temperature and moisture conditions are expected to be suitable for growth. The final ranges will also be influenced by patterns of disturbance (e.g., fire and insect outbreaks), species interactions with native and non-native species, and landscape structure and the movement capabilities of the plant species, which will interact to determine the distribution and abundance of species in the future.

Shrubland/rangeland

Sagebrush steppe is the dominant low and mid-elevation vegetation of the interior Columbia Basin. This community type is predicted to change greatly in range and extent under future climatic conditions. Big sagebrush *(Artemisia tridentata*), the most widespread and characteristic shrub of the inner Columbia Basin, is expected to decline sharply throughout the region (e.g., Hansen and Dale 2001, Shafer et al. 2001). Sagebrush is found in regions where most precipitation falls in winter, and sagebrush has both ephemeral and perennial leaves that allow them to take advantage of this pattern (Welch 2005). Although the range of big sagebrush remains very large, occurrence of big sagebrush is already sharply reduced from that of 100 years ago by the conversion of shrubland to agricultural uses, including rangeland, and by the high degree of fragmentation of remaining sagebrush habitat (Welch 2005, Knick et al. 2003). Millar et al. (2006) show that the interior shrublands/grass-lands also are likely to be impacted by expansion of woodlands (e.g. Ponderosa pine) or continental conifer forests (e.g., Douglas fir), due to increased precipitation, enhanced water-use efficiency for elevated CO_2 and a lengthening of the growing season. The range of big sagebrush is predicted to shift to Canada, with shrubs now found in the southwestern United States replacing it throughout much of the Columbia Basin in the United States. (Hansen and Dale 2001, Shafer et al. 2001).

Wildlife Species

Prediction of effects of global warming is more complicated for wildlife, which depend not only on suitable conditions of temperature and moisture but also on the resulting vegetation for habitat and often for food. Thus, there is an additional layer of effects to be accounted. Paleoecological studies show clearly that the responses of both plants and wildlife to climate are species specific, so local assemblages of species are expected to be different in the future from what we know today (Graham and Grimm 1990, Jackson and Overpeck 2000). An additional concern comes from the many non-native species now present in the Pacific Northwest or surrounding areas of North America. As these change their ranges in response to climate, novel predator-prey interactions and new sets of competing species will occur, with outcomes that we cannot anticipate (e.g., Schmitz et al. 2003). The main lesson of the many studies of expected climate-caused changes in wildlife is that we must be prepared to accommodate major surprises (Root and Schneider 2002). Thus, a commonly recommended strategy for preparing to mitigate effects of climate change is to plan for a high degree of uncertainty rather than for a more narrow solution that might appear optimal today.

The effects of changing climate on wildlife are expected to be strongly interactive with changes in habitat caused by changing land use. The expansion of population in the West, including expanding habitation that outstrips population growth through growing numbers of second homes, will result in decline in available habitat for most wildlife (excluding those that benefit directly from the kinds of environments that are created by people) and in increased fragmentation of remaining habitat. An example of the expected problems for wildlife that will accompany global warming and changing human population can be drawn from the sagebrush habitat of the inner Columbia Basin, which is highly fragmented, has increasingly high numbers of non-native plant species, and has had sharply increasing frequency, size, and intensity of fire in recent years. Many species of sagebrush birds and mammals are of concern to the Columbia River Basin Fish and Wildlife Program, including the greater sage grouse, Columbian sharp-tail grouse, pygmy rabbit, Brewer's sparrow, sage sparrow, and sage thrasher, all of which have population declines and populations of concern in at least some Columbia River Basin states. The bird species of shrubland and grassland are declining more rapidly than any other group of species in North America (Knick et al. 2003). A survey of 61 species of birds and small mammals that are dependent on sagebrush habitat (43 upland species and 18 riparian species) found that a majority of populations had either significantly declined or were not present in censuses of areas thought to be suitable habitat (Dobkin and Sauder 2004).

One important specific strategy to mitigate against damaging effects of climate change is the identification of locations likely to remain suitable for particular wildlife and retention of sufficiently large tracts of land within these regions to enable persistence of these species. These protected areas also must be linked to enable seasonal movements and longer-distance, more permanent range shifts. Preservation of suitable vegetation that is naturally occurring under future climate conditions will require similar attention to protection of large areas that cover a range of linked climatic conditions (e.g., latitudinal and altitudinal variation to avoid unnecessary habitat fragmentation that would both increase local extirpation and decrease possibilities of migration of plants and animals to new ranges matched to future local climates).

Effects on Tributary Habitat

Changes in hydrology and temperature caused by changing climate both have the potential to negatively impact aquatic ecosystems in the Columbia basin with salmonid fishes being especially sensitive to projected changes. The intensity of the effects will vary spatially. However, climate change does have the potential to generate ecological responses in virtually all the tributary systems of the Columbia Basin.

The potential impacts of climate warming on stream habitat have been assessed (EPA 1995; Eaton and Scheller 1996; Rahel et al. 1996; O'Neal 2002; Preston 2006). Several of these reports include information relevant to the Columbia Basin. Rahel et al (1996) projected losses of 7% to 76% of the trout habitat in the North Platte River drainage in Colorado as a result of warming. Although the North Platte River is outside the Columbia Basin, the conditions in this Rocky Mountain system are comparable to many of the tributaries of the Columbia in Idaho and Montana.

O'Neal (2002) provides a detailed assessment of the potential impacts of climate warming on salmon and trout habitat in the contiguous 48 states of the United States and also provides specific projections for the Pacific Northwest. This analysis was conducted using the Canadian Climate Center CGCM2 model and an assumption of continued increase in atmospheric CO_2 at a rate described in the A2 scenario (Nakicenovic et al. 2000). This combination of model and emissions scenario produces a fairly high projection of climate warming with a 5^oC increase in average global temperature by 2090. Those locations that experienced a projected average weekly maximum temperature that exceeded the upper thermal tolerance limit for a species were considered to be lost habitat. The results suggest a substantial decline in the habitats suitable for cold water fishes. For example, areas with thermal conditions suitable for trout would decrease by 15% to 40% by 2090 across the United States. In the Pacific Northwest 2% to 7% of current trout habitat would be unsuitable by 2030, 5%-20% by 2060 and 8% to 33% by 2090. Salmon habitat may be more severely affected, in part because these fishes can only occupy areas below barriers and are thus restricted to lower, warmer elevations within the region. Salmon habitat loss would be most severe in Oregon and Idaho with potential losses exceeding 40% by 2090 (Fig. 9). Loss of salmon habitat in Washington would be less severe; worst case of about 22% loss by 2090. These estimates do not consider the associated impact of changing hydrology.

A recent analysis of the impact of climate warming on cold-water fish habitat applied a Monte-Carlo simulation to climate projections from multiple General Circulation Models and future greenhouse gas emission scenarios (Preston 2006). This approach was chosen to account for the uncertainty associated with future predictions of climate change. The median values for proportion of cold-water fish habitat lost in the Rocky Mountain region for the years 2025, 2050 and 2100 were 20%, 35% and 50%, respectively. Considerable variability was associated with these estimates (95% confidence intervals - 2025: 15% - 35%; 2050: 22%-58%; 2100: 20%-100%). Nonetheless, all combinations of models and greenhouse gas scenarios indicated a substantial loss of coldwater fish habitat in this region.

Although there is considerable uncertainty about how severe or widespread the loss of cool-water fish habitat will be in the Columbia Basin, there is compelling and growing evidence to indicate that significant changes in the quality and quantity of habitat suitable for salmon, trout, and cool-water species will occur. Sites most susceptible to effects from higher summer water temperatures would include those locations that currently experience high summer air temperatures. Lower elevation areas, locations east of the Cascade Mountain crest and in the southern portions of the Columbia Basin would be expected to be most affected (Fig. 9). Changes in hydrology will most affect tributary habitats in those watersheds where snow levels are impacted. Watersheds that are just above the current snow line currently may experience a change from a snow melt dominated hydrologic regime to one that is driven primarily by rainfall or rain on transient snow pack. Even those watersheds that remain above the snow line will experience earlier snow-melt runoff. These changes in hydrology all may have associated impacts on salmon and trout productivity.

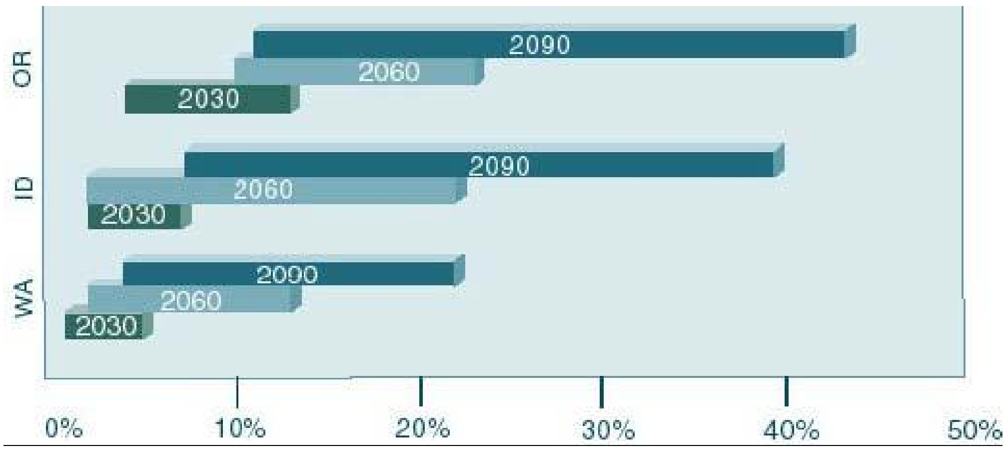


Figure 9: Proportion of salmon habitat lost in the future in WA, OR and ID as a result of warming associated with climate change from O'Neal (2002). The projections represent output from the Canadian Climate Center CGCM2 model and an assumption of continued increase in atmospheric CO_2 at a rate described in the A2 scenario (Nakicenovic et al. 2000). This combination of model and emissions scenario produces a fairly high projection of climate warming with a 5°C increase in average global temperature by 2090.

Hydrologic changes to Columbia Basin streams will be driven primarily by reduction in snow pack as temperatures warm, and the snowline moves upward. The result of these changes will be higher frequency and intensity of flood flows; earlier occurrence of snow melt runoff and soil moisture recharge; reduced natural summer and early autumn flows; and an increase in the duration of the summer dry period with very low soil moisture (Hamlet 2006). Natural tributary flow regimes will be most altered in those watersheds at mid-elevations where higher freezing level causes a change from a snowmelt-dominated to a rainfall-dominated flow regime (Hamlet 2006).

There will be some watersheds that may not be subjected to large changes in flow regime, even in areas affected by elevated snow level. In areas with permeable geology, like volcanic fields, precipitation, either as snow or rain, enters into an extensive groundwater reservoir. Water may be stored for years or decades and outflow from the aquifer is very stable, resulting in little seasonal change in flow. Watersheds such as the Deschutes and Metolius rivers in Oregon exhibit this type of hydrologic system. Flows in watersheds with these extensive groundwater systems will be modified much less by reduced snowpack as long as the total amount of precipitation does not decrease (O'Conner et al. 2003; Jefferson et al. 2006). Such streams that are sourced from deeper groundwater reservoirs maintain much cooler summer temperatures than those supplied by shallow subsurface flows (Tague et al. in press). However, watersheds fed by these very large groundwater systems are relatively uncommon in the Columbia Basin.

Increase in regional air temperatures and low stream flows will be the primary driver of increased water temperatures. The most affected watersheds will be those that typically experience warmer summer temperatures (O'Neal 2002) including streams at lower elevations and those with channel conditions prone to heating (wide, shallow, lack of riparian vegetation) (Crozier and Zabel 2006). Many of the most sensitive streams are located in eastern Washington and southern Idaho (Fig. 10). Crozier and Zabel (2006) reported that despite high elevation, stream temperatures in the Salmon River basin already exceed 13°C and some streams have annual temperatures that are rising steadily about 1.2°C per decade. Changes in water temperature also are linked to hydrologic changes. Lower summer and early autumn flows will make streams more responsive to increased air temperature and earlier snow melt will enable warming to begin earlier in the year.

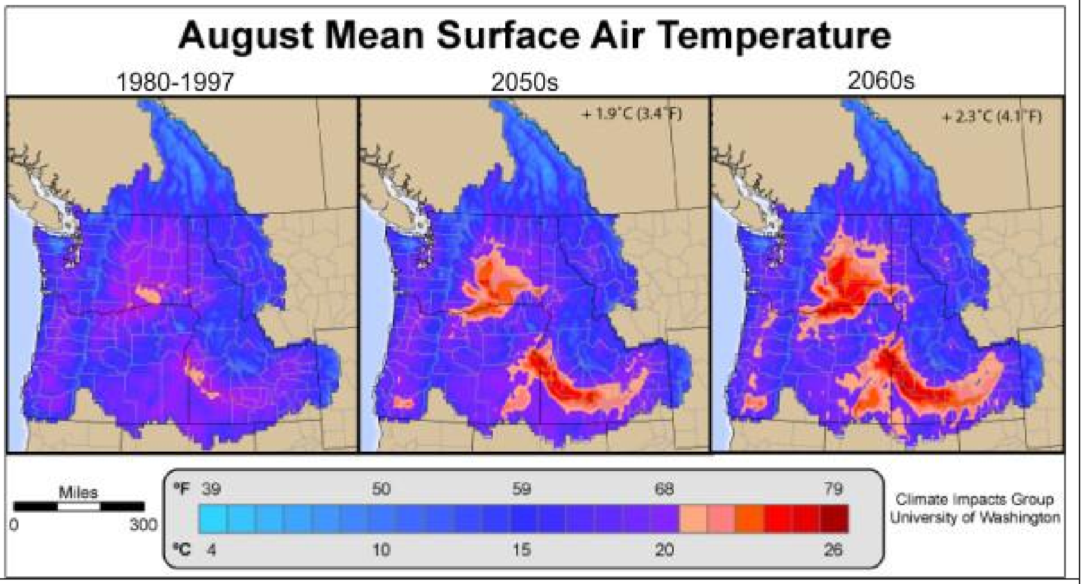


Figure 10: The warmest temperatures in the Columbia River basin are typically observed in August in the lower Columbia and Snake Basins. The monthly average August temperature maps shown below highlight those parts of the region that have experienced August mean temperatures greater than 20C for 1980-97, and for periods experiencing

+1.9C and +2.3C warming, temperature changes that are in the middle of projected temperature change scenarios for ~2050s and ~2060s. Note that only a few percent of the region had August mean temperatures greater than 20C in the 1980-97 period, but about 20% of the region would have August temperature greater than 20C with 2.3C of warming.

As discussed in the section in this report on potential effects on terrestrial ecosystems, climate change may increase the severity and frequency of both fires and insect infestations, which are likely to affect aquatic habitats as well. Removal of trees from riparian areas by fire or insects will lead, at least temporarily, to an increase in solar radiation reaching the water and exacerbate the water temperature increase associated with climate warming (Beschta et al. 1987). Late summer flow may be increased by the loss of tree cover due to reduced transpiration (Ziemer and Lisle 1998). Higher summer flows may offer some benefit to aquatic biota, provided that water temperatures are not limiting. However, it is not clear whether the increase in flow due to reduced transpiration would be sufficient to offset reduced flows related to earlier snowmelt runoff and any benefit would be of short duration, decreasing as vegetation reoccupied the watershed (Hicks et al. 1991). Reduction in tree cover also may lead to increased snow accumulation and earlier and more rapid melting (Harr 1986). These changes would further contribute to an earlier period of high flow in the basin. Sediment production and delivery to streams also may be increased as loss of vegetative cover can lead to increases in mass soil movements such as landslides and debris torrents (Benda et al. 1998). Some the of the highest quality aquatic habitat remaining in the Columbia Basin is found in forested areas. Therefore, increased incidence of fire and insect outbreaks will disproportionately impact habitats of key importance to native fish and wildlife populations.

The projected changes in thermal and hydrologic conditions have the potential to affect salmonid fishes during all their freshwater life history stages. These potential impacts are discussed below.

Egg Incubation and Fry Emergence

Increased frequency and severity of flood flows during winter can affect over wintering juvenile fish and eggs incubating in the streambed. Eggs of fall and winter spawning fish, including Chinook, coho, chum, and sockeye salmon and bull trout, may suffer higher levels of mortality when exposed to increased flood flows (Jager et al. 1997). Scouring of the streambed can dislodge the eggs (Schuett-Hames et al. 2000) and elevated sediment transport caused by high flow can increase sediment deposition in redds, suffocating eggs (Peterson and Quinn 1996). Spring spawning fish, such as steelhead and cutthroat trout, also may suffer increased egg mortality due to dewatering of redds caused by earlier snow melt runoff (Jager et al. 1997). Shifts in the timing and magnitude of natural runoff will likely introduce new selection pressures that may cause changes in the most productive timing or areas for spawning.

Warmer winter temperatures and the retreat of snow level to higher elevations may lead to earlier fry emergence for some populations (Healey 2006). Individual populations have spawning times and egg development rates that are matched to the environmental conditions of their spawning stream (Tallman 1986, Beacham and Murray 1990). Earlier emergence may expose the fry to increased mortality rates due to a lack of food or increased predation (Brannon 1987; Tallman and Healey 1994). Increased water temperature also may increase the metabolic rate of the developing embryos, causing them to divert energy from growth to metabolic maintenance. This process would result in smaller fry size at emergence (Beacham and Murray 1990). It is also possible in some situations that elevated incubation temperatures could cause direct egg mortality or increased susceptibility to disease (Healey 2006).

Bull trout (*Salvelinus confluentus*) in the Columbia Basin require cold, headwater streams for spawning. Therefore, a warming climate may disproportionately impact this species. Recent projections of the loss of habitat suitable for bull trout in the Columbia Basin as a result of climate warming range from 22% to 92% (B. Reiman, USFS, pers. comm.). The areas most severely affected are at lower elevations. Reduction in bull trout spawning habitat also will further fragment existing populations and reduce the opportunity for genetic exchange, which may accelerate the decline of this species in the Columbia Basin beyond that predicted simply due to temperature change.

Spring/Summer Rearing

Reduction in spring and summer stream flow in watersheds where snow pack has been reduced and snow melt timing advanced may impact the quality of rearing habitat. Reduction in summer and early autumn flows will, at a minimum, reduce the area of wetted stream channel, thereby reducing available habitat for rearing fish. In addition, susceptibility to predation may be increased due to shallower water or stranding of fish in isolated pools. Fall stream flow was found to be positively associated with survival in some populations of Salmon River Chinook salmon populations (Crozier and Zabel 2006). The populations sensitive to these flow changes tended to occupy cooler streams with narrow channels while survival of populations in wider, warmer streams was more closely related to summer temperature.

Warmer water temperatures during summer can have a variety of effects. Salmonids may be excluded from reaches with temperatures that are already close to their upper thermal limit (O'Neal 2002). Even in systems where water temperatures do not exclude use by salmonids, metabolic rates will increase. In systems where food is limited, the increased energy required for metabolic maintenance will reduce growth rates leading to smaller size at the end of the summer (Marine and Cech 2004). Smaller fish typically suffer higher mortality rates during winter than larger fish (Quinn and Peterson 1996). Both native and non-native fishes may enjoy a competitive advantage over salmonids at elevated water temperatures. Brook trout (*Salvelinus fontinalis*) have been shown to be more efficient at obtaining food than cutthroat trout at 20°C but the two species exhibited comparable ability to obtain food at 10°C (DeStaso and Rahel 1994). Redside shiners (*Richardsonius balteatus*) have been shown to displace steelhead from preferred habitat locations at higher water temperatures (Reeves et al. 1987). Northern pikeminnow

(*Ptychocheilus oregonensis*) also prefer warmer temperatures than salmonids and may become more numerous in rearing areas of juvenile salmonids as stream temperatures increase (Petersen and Kitchell 2001).

In some streams an increase in temperature may improve conditions for salmon and trout. In very cold streams, time of spawning and egg incubation may be delayed until well into summer resulting in small fry at the onset of winter and reduced survival (Harig and Fausch 2002). Increased spring and summer water temperatures caused by climate change could alleviate this problem to some extent by enabling earlier spawning and fry emergence and a longer growth period. Thus, fish would be larger at the end of summer provided adequate food is available. Winter mortality associated with anchor ice also might be reduced (Meisner at al. 1988). These types of positive effects would likely be limited to aquatic systems at the highest elevations in the Columbia Basin and would influence few stream occupied by anadromous species. However, Beckman et al. (1998) found that increased temperatures led to higher growth rates and earlier downstream movements of yearling Chinook salmon, which may provide a survival advantage under some circumstances.

Predation rates on juvenile salmon can be affected by elevated temperatures. If water temperature remains below 20^oC, increased activity by predators may be partially offset by increased activity of juvenile salmon, enabling them to better avoid predators. However, juvenile Chinook salmon have been shown to become less adept at avoiding predators at temperatures above 20^oC (Marine and Cech 2004). The consumption of prey by many piscivorous fishes continues to increase above 20^oC. Petersen and Kitchell (2001) used a bioenergetics model to assess the effect of temperature on predation by northern pikeminnow on juvenile salmon. They used temperature records from the Columbia River for the years 1933-1996. Their analysis suggested that during warmer years predation rates were 26% to 31% higher than during the coldest years. Predation rate during the single warmest year was predicted to be 68% to 96% greater than during the coldest years. Increases in predation on young salmon by other piscivorous fishes in the Columbia Basin also would be expected to increase if temperatures were elevated to stressful levels (Petersen and Kitchell 2001).

Overwinter Survival

Increased winter water temperatures may have both positive and negative impacts on fish. Higher winter temperatures may enable fish to feed more actively during the winter, potentially increasing growth rates if sufficient food is available. If food is in limited supply, the elevated metabolic demands created by elevated winter temperatures could reduce winter growth rates and contribute to reduced smolt size the following spring (Healey 2006). Higher winter temperatures also would increase the activity of predators, possibly increasing mortality due to this source (Petersen and Kitchell 2001).

Climate change effects experienced by fish during the spring and summer also can affect their ability to survive through the winter. Generally, higher summer temperatures will reduce the growth rates of juvenile fish, reducing average size entering winter. Body size at the end of summer has been shown to be positively related to overwinter survival

(Quinn and Peterson 1996). As noted above, in certain circumstances higher water temperatures during spring and summer may accelerate growth, if sufficient food is available to offset the higher metabolic cost associated with elevated temperature. This effect is likely to occur most frequently in cold, high-elevation streams.

Where the hydrologic regime changes from snow melt dominated to rain dominated, more frequent high flows could occur. These circumstances are likely to cause increased mortality if winter habitat that provides refuge from floods is not available. This type of habitat is often located on floodplains in the form of low-gradient tributaries or ponds (Peterson 1982). As floodplain habitat along many of the major rivers in the Columbia Basin has been modified or isolated from the channel, refuge habitat is likely to be very limited (Bottom et al. 2006). Therefore, the hydrologic changes during winter associated with climate change would be likely to elevate mortality.

Effects in the Mainstem

Physical Effects

Hydrosystem development on the mainstem Columbia and Snake rivers has altered these free-flowing rivers into a series of reservoirs, and along with other anthropogenic land-use and water-use practices has already altered seasonal water temperature regimes and flow patterns from historical conditions in the basin. With the completion and coordinated operation of the major Columbia Basin storage dams in the 1960s and 1970s, peak daily flows at The Dalles were substantially and systematically reduced, while flows from October through April have been substantially and systematically increased (Figure 11; Naik and Jay (2005)). The net result of hydrosystem operations has been to reduce the historic peak flows in May, June, and July and to increase winter flows on a regular basis. Note that the changes in mainstem flows due to hydrosystem operations since at least the 1970s are substantially greater than the natural runoff changes projected to be caused by climate warming in the 21st century.

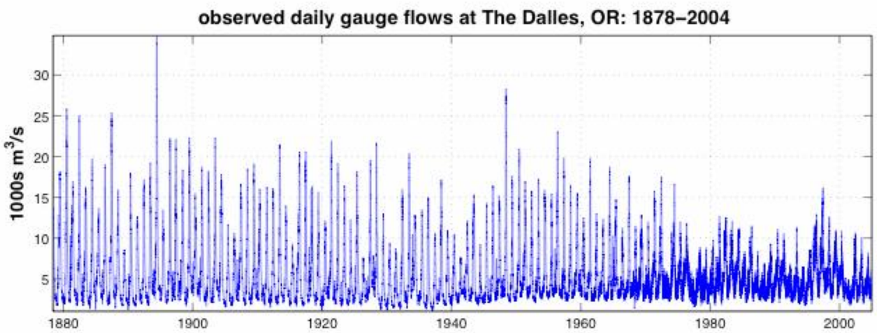
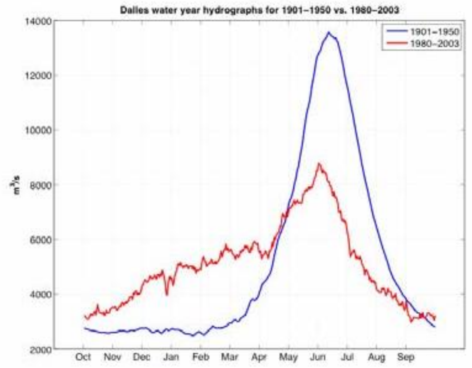


Figure 11: (top) The observed daily average gauge flow at the Dalles, Oregon, from 1878-2004, in m3/s. (right) Average daily hydrographs at the Dalles for 1901-1950 (in blue) and 1980-2003 (in red). Note that both figures show the major reduction in daily peak flows, primarily a consequence of hydrosystem development and operations, but also influenced by irrigation withdrawals and climate variations (Naik and Jay 2005).



Management of the hydrosystem also causes substantial changes in stream flow at time scales shorter than one day. In the Hanford Reach section of the mainstem Columbia, daily fluctuations below Priest Rapids dam in the relatively low-flow months of summer and fall often have double the flow during daylight hours compared to flows at nighttime (Figure 12).

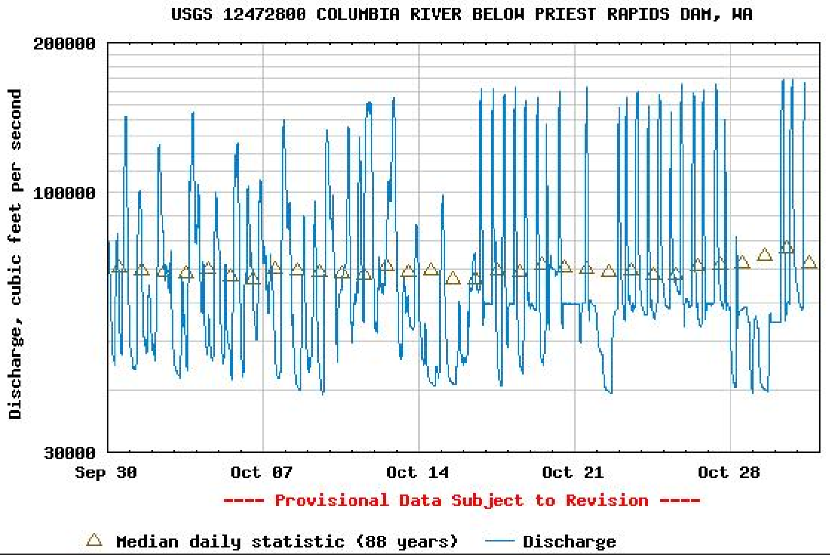


Figure 12. USGS gauge flows in the mainstem Columbia River below Priest Rapids Dam, WA, from September 30 though October 30, 2006. Note that on most days daily flows range from lows of ~40,000 cfs to highs of ~160,000 cfs. Figure obtained from the USGS web-pages (http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12472800).

Long-term temperature series data were collected at Bonneville Dam (1938-1996) and Rock Island Dam (1933-1996) on the Columbia River (Fig. 13) to characterize how upper and lower mainstem river temperature change may have effected historical trends in predation rates on salmonids through a bioenergetic analysis (Petersen and Kitchell

2001). Trends as seen in Figure 13 indicate that water temperatures were relatively warm in the 1930s, cooler in the late 1940s to 1950s, and gradually warmed from about 1960 to 1996. If we were to plot temperatures from 1996 to the present we would see a definite trend in this increasing warming.

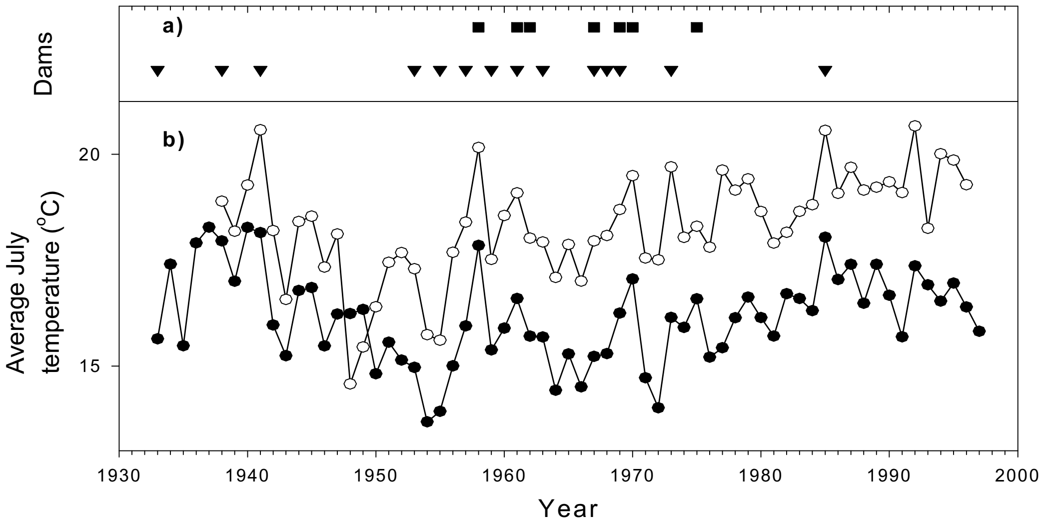


Figure 13. Average daily water temperature during July at Bonneville (O) and Rock Island (●) dams from 1933 to 1996. Also shown is the year of construction for dams on the lower Snake River (ν) and the Columbia River (τ; U.S. and Canadian dams). From Petersen and Kitchell (2001).

The construction of the hydrosystem has also altered mainstem water temperature regimes. Currently, warming of water in the reservoirs begins earlier in the spring and persists longer into the fall than historically (Quinn and Adams, 1996). Climate modeling of future water temperatures in the Columbia and Snake rivers predicts an increase of 1^o C or greater by 2040 (Hamlet and Lettenmaier 1999; Payne et al. 2004). The models also predicted an increase for winter precipitation of about 5% by 2040, with more falling as rain and less as snow, reducing winter snow accumulation, thus increasing winter to early spring flows and extending the low summer flow period to winter (Payne et al. 2004). The construction of the hydrosystem has also altered mainstem seasonal water temperature patterns. Currently, warming of water in the reservoirs begins earlier in the spring and persists longer into the fall than historically (Quinn and Adams, 1996).

Biological Effects – Juvenile Salmonids

Climate change effects will have the most significant impacts on the early life stages of fall Chinook, which rear in mainstem habitats in the Hanford Reach of the Columbia River and in the lower Snake River above Lower Granite Dam (LGR). As the early life stages of spring/summer Chinook salmon, coho salmon and steelhead are spent primarily in tributary habitats within the Columbia River Basin, impacts on those types/species from climate change will be most pronounced there, as indicated in the previous section of the report.

Increased rate of embryonic development and earlier emergence

Increases in water temperature during egg incubation will increase the rate of development and lead to an earlier hatch and emergence and most likely at a smaller average size than historically (Healey 2006). Smaller sized fry are likely to have lower survival due to increased vulnerability to predators (size selective predation and swimming performance) and increased maintenance metabolism leading to greater food demand, slower growth, and increased risk to predators due to added foraging time (Healey 2006). Earlier life stage timing may also lead to earlier smoltification and emigration timing, which may adversely affect optimal ocean entry.

Contraction of juvenile fall Chinook summer rearing habitat due to temperature increases and decreased flow

Water temperature was the most important variable effecting presence of subyearling fall Chinook in the shoreline habitats of the Hanford Reach, Columbia River (Tiffan et al. 2006). These juvenile fall Chinook preferred shallow, relatively warmer water than occurs in the main channel waters of the Columbia River in this reach. However, climate change will likely increase water temperatures in shallow shoreline areas beyond their preferred temperature of 17^{o} C (Sauter et al. 2001) and earlier in the season. At these higher temperatures, survival of wild subyearling generally decreases with increasing water temperatures (Connor et al. 2003). Juvenile fall Chinook will then likely move out of protected shallows earlier and potentially at a smaller size than normal for this risky transition. This may lead to a size-related increase in exposure and vulnerability (size related) to predators (Petersen and Kitchell 2001) (see below in predation section) and cause a decrease in growth rate if food resources are limited in less optimal habitat in down-river reaches. However, if the food base is equivalent or better in down-river habitats, growth rates would be increased with higher temperatures and potential negative effects could be compensated for.

Alteration in timing of smolt migration

Earlier snowmelt and earlier, higher spring flows and warmer temperatures may cause spring Chinook and steelhead yearlings to smolt and emigrate to the estuary and ocean earlier in the spring. This early emigration may cause these juveniles to arrive in the estuary and ocean either during favorable upwelling conditions, or prior to the period of favorable ocean upwelling if upwelling is delayed (see section on upwelling). For spring Chinook, upwelling during April has been correlated with enhanced survival (Scheuerell and Williams 2005). Yearling migrants also may be exposed to increased predation risk in the mainstem because of higher consumption rates by predators at the elevated spring water temperatures (see below in subsection on predation).

Increased water temperatures also may lead to faster growth rates, which may further contribute to earlier smoltification and emigration timing (Beckman et al. 1988). Smolt size is an important determinant of marine survival for some species, such as coho salmon (Bilton et al. 1982; Holtby et al. 1990). However, Henderson et al. (1992) found for pink salmon, *O. gorbuscha*, date of ocean entry timing, not size, was the primary determinant of survival, not size. Earlier outmigration may be advantageous for some stocks of in-river fish that now have poor survival due to delayed ocean entry (Snake River spring/summer Chinook), provided that upwelling and ocean conditions are favorable during entry.

Another consequence of elevated spring water temperatures is that when water temperatures rise to above 13 ^{0}C, gill ATPase (an indicator of migratory readiness) in yearling steelhead emigrants decline and these fish often stop downstream migration and residualize over winter (Zaugg and Wagner 1973). In addition to having consequences for survival and stock productivity, this behavior confounds PIT tag survival estimates because steelhead that hold-over are counted as mortalities. For example, during the 2001 juvenile salmonid emigration, under extremely low flows and relatively high temperatures, survival of Snake River juvenile steelhead was only 4.2% from Lower Granite to Bonneville (Zabel et al. 2002). Zabel et al. (2002) indicated that the residualization of large numbers of steelhead juveniles below Lower Monumental Dam may have been a big cause for this low survival estimate. During the following spring migration only 0.15% of these 2001 PIT tagged fish were detected indicating that few survived predators or fisheries, and there were too few to substantially alter survival estimates for 2001.

Temperature increases and decreasing flow in summer may also lead to earlier migration timing of both Columbia and Snake river populations of “ocean-type” fall Chinook. Thermal changes could be particularly damaging to the portion of the Snake River juvenile fall Chinook population that exhibits a “reservoir-type” life history Chinook. Research by Connor et al. (2002; 2003; 2005) has indicated that when water temperatures are warmer during the incubation period of fall Chinook eggs the timing of the various life history stages (emergence, parr, and smolt) occur earlier. Cool water flow augmentation from Dworshak Reservoir has led to lower water temperatures in the spawning areas for fall Chinook in the lower Snake River and may be an important factor in the development of the reservoir-type life history (Connor et al. 2003). Flow augmentation also maintains cooler summer and fall water temperatures, providing thermal refugia for the rearing reservoir-type Chinook. If water temperatures in the lower Snake River warm during spring, summer and fall sufficiently that the cannot be maintained at a level suitable for salmon by cold water releases from Dworshak Reservoir, the reservoir-type fall Chinook populations of the lower Snake River may be diminished or lost.

Decreased flow owing to earlier snowmelt runoff may cause delay in migration of juvenile fall Chinook in the forebays of mainstem dams if summer spill is reduced. This could lead to higher predation rates in the forebay. It has also been shown that in low flow periods in the summer there is some temperature stratification in the near dam forebay (Bennett et al. 1997). With warmer waters near the surface, juvenile salmonids may alter their vertical distribution by moving to deeper cooler waters and be less efficiently passed through surface collection devices (e.g. removable spillway weirs (RSWs)).

Changes in predation on juvenile salmonids

If juvenile salmonids of all life history types emerge from spawning gravels earlier due to increased winter water temperatures, fry size may decline. Smaller fry are more vulnerable to predation by northern pikeminnow, which are generally size selective when feeding on juvenile salmonids (Poe et al. 1991). Also as indicated above, if juvenile salmonids of any life history type leave preferred rearing habitats too early this may reduce growth rates and result in increased vulnerability to predators.

Predicted increases in water temperature in Columbia and Snake River reservoirs during the major smolt emigration will most likely increase consumption rates and growth rates of predators and hence predation related mortality. Summer emigrants, primarily subyearling fall Chinook, are particularly vulnerable. Juvenile salmonid consumption rates of the three major predators (northern pikeminnow, walleye, and smallmouth bass) in Columbia and lower Snake River reservoirs is highest in July concurrent with maximum availability and temperature (Vigg et al. 1991) and the maximum daily consumption of juvenile salmonids by northern pikeminnow increases exponentially as a function of temperature (Vigg and Burley 1991). Sublethal thermal stress is another factor known to increase vulnerability to predation (Coutant 1973; Yocum and Edsall 1974). Thermally stressed fish may suffer elevated mortality when exposed to the additional physical stress associated with dam passage. The combined effects will likely increase the vulnerability of surviving fish to predators (Mesa et al. 1994; Mesa 1994).

Another indication of how predation rates on juvenile salmonids emigrating through the Columbia River Basin may increase with projected climate change is revealed in a bioenergetics analysis by Petersen and Kitchell (2001). They examined climate regime shifts and corresponding water temperatures in the Columbia River from 1933-1996 to estimate how predation, primarily by northern pikeminnow, on juvenile salmonids may have varied. Three indices of climate, the Pacific Decadal Oscillation (Mantua et al. 1997), the Pacific Northwest Index (Ebbesmeyer and Strickland 1995), and the Columbia Basin Index (Petersen and Kitchell 2001) were used to characterize historical climate conditions for the Columbia River Basin. All three indices were highly correlated and agreed that climate shifts occurred in 1946, 1958, 1969, and 1977. Summer water temperature varied as much as 2^{o} C between different climate periods. Their results from the bioenergetics model indicated that predation on juvenile salmonids was estimated to be from 26% to 31% higher during warmer spring-summer periods (1933-1946, 1978-1996) than during a much colder period (1947-1958) (Fig. 14). Their results also indicated that predation on salmonids by walleye and smallmouth bass would have varied in a very similar manner to that of pikeminnow.

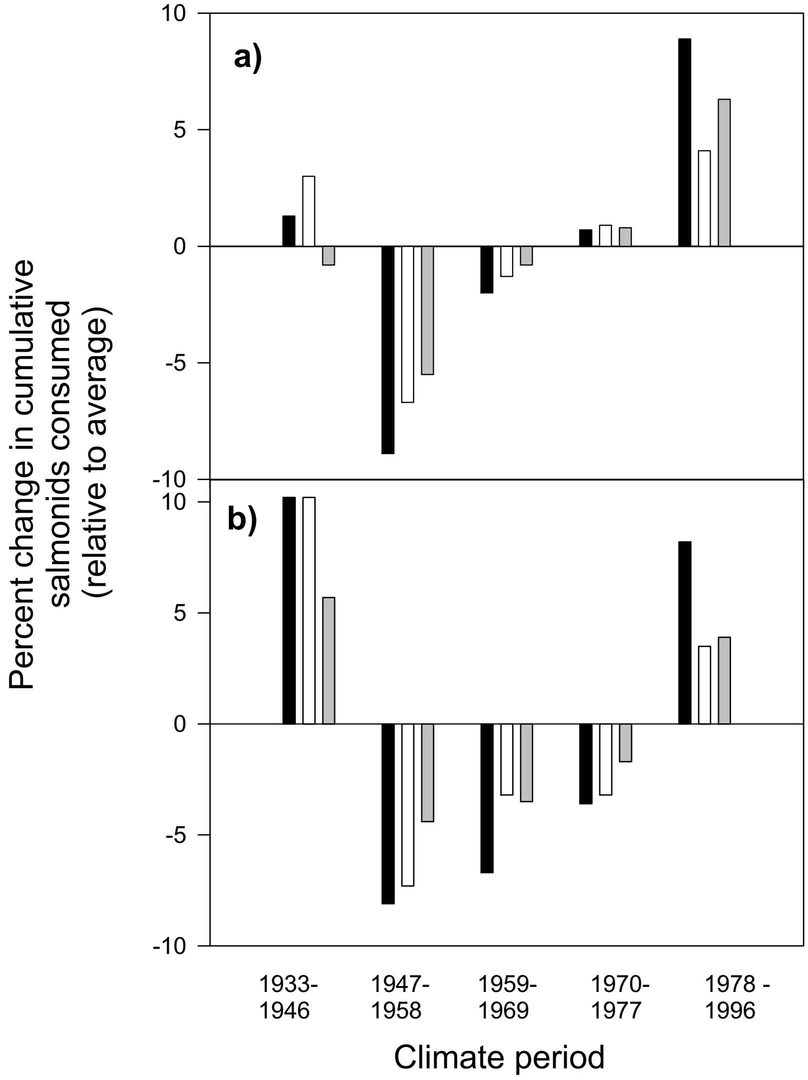


Figure 14. Percent difference (relative to the overall average) in cumulative, per capita consumption of salmonids in the Columbia River by northern pikeminnow (black bars), smallmouth bass (white bars), and walleye (gray bars). Estimates were made using bioenergetics models and water temperature from Bonneville (a) and Rock Island (b) dams. (modified, with permission, from Petersen and Kitchell, 2001).

Changes in smolt health (pathogens and parasites)

Many fish pathogens and parasites are common in the environment and their salmon hosts but often don't become injurious until their host becomes thermally stressed. One consequence from long-term chronic exposure of smolts to increased water temperatures is an increase in the risk of high mortality in the forebays and collection systems of mainstem dams due to a bacterial gill disease, *Cytophaga* (formerly *Flexibacter*) *columnaris*. This disease has the potential to kill very large numbers of smolts in a few days and has been documented as occurring at McNary and John Day dams by the smolt monitoring program (Martinson, Rick, et al. 1993 -1996 BPA Annual Reports).

Another common pathogen known to infect wild and hatchery salmonids in the Columbia River Basin is *Renibacterium salmoninarum* commonly known as bacterial kidney disease (BKD) (Sanders et al. 1992). In a study examining BKD prevalence and severity in juvenile hatchery spring Chinook in the Columbia and Snake rivers (Maule et al. 1996) the results indicated that for juveniles emigrating from the Snake River hatcheries to the mainstem dams the severity of BKD increased significantly more than for infected Columbia River hatchery fish emigrating from the hatcheries to the mainstem dams. One of the conclusions from this study was that the temperatures experienced by fish emigrating in the Snake were considerably warmer than in the Columbia which may have caused the difference. Future increasing water temperatures may increase the frequency of occurrence and severity of BKD infections in salmonids throughout the Columbia River Basin.

Biological Effects – Adult Salmonids

Changes in immigration behavior, dam passage, and survival

Predicted future increases in water temperature are of particular concern for the return of migrating adult spring, summer, fall Chinook, sockeye, and summer steelhead (many of them ESA listed ESUs) in the Columbia and Snake rivers. Average water temperatures in the summer currently often exceed 18° C in the lower mainstem Columbia River and may exceed 21° C in the lower Snake River (McCullough 1999). Water temperature is likely the most important variable affecting the migration behavior, physiology, and spawning success of adult Chinook salmon and steelhead (Groot and Margolis 1991), and there is a considerable body of literature dealing with the indirect and direct effects of temperature on adult salmonids. Richter and Kolmes (2005) reported the upper optimal temperature for adult salmonid migration to be 18° C. Marine (1992) suggested that an incipient upper lethal temperature limit for pre-spawn adult salmonids was 17° C to 20° C and McCullough et al. (2001) indicated that exposure of adult salmonids to constant temperatures of 21° C to 22° C for one week was lethal.

The migrational timing and behavior of adult salmon and steelhead in the Columbia and Snake rivers has been linked to optimal or preferred water temperatures and immigration rates appear to increase up to about 16 ° C and then decline as temperature goes higher (Salinger and Anderson 2006). Spring Chinook migrate through the Columbia and Snake rivers when water temperatures are near optimal and usually avoid thermal stress problems. However, when summer water temperatures are higher than average, fall Chinook and steelhead have been documented to stray into cooler water in Columbia

River tributaries (Goniea et al. 2006, High et al. 2006). Fall Chinook and steelhead have also been found to delay entry into the Snake River (often several degrees warmer than the mainstem Columbia) until temperature conditions are suitable to continue migration (Perry et al. 2002).

Some of the potential impacts from increased water temperatures on immigrating adult salmon passage at mainstem hydroelectric dams include delay in passage and failure to enter fish ladders due to higher temperatures in ladders (Caudill et al. 2006), increased fallback (ref.), and loss of energy reserves because of increasing metabolic demand with increasing temperatures (Geist et al. 2003). Any or all of these factors may add to pre-spawn mortality or lack of spawning success.

Since 1991, cold-water releases from Dworshak Reservoir have been made to reduce in-river water temperatures in summer for emigrating fall Chinook juveniles and fall Chinook and steelhead adult migrants. Clabough et al. (2006) found that tagged (temperature and depth acoustic tags) adult salmon and steelhead actively sought out and used these cooler waters, reducing the probability of thermal stress in the lower Snake River. In the future as water temperatures continue to become warmer and persist longer into fall, these delays may become more frequent and last longer unless cold water releases from Dworshak Reservoir can continue to moderate this warming.

Changes in adult salmonid health (pathogens and parasites)

Many fish pathogens and parasites commonly infect adult salmon but often don't become injurious until their host becomes thermally stressed. A classic example of this was the 2002 Klamath River fish-kill, where over 33,000 adult salmon (primarily fall Chinook) died in the lower 36 miles of the river (California Department of Fish and Game 2003). The primary cause of this fish-kill was a combined outbreak of ich (the ciliated protozoan, *Ichthyopthirius multifilis*) and columnaris (the bacterial gill disease, *Cytophaga (*formerly *Flexibacter columnare*). However, other important factors which led to this outbreak were high water temperatures, atypically low river flows, and high fish densities which led to rapid transmission of disease.

Another case where increasing water temperatures may have led to parasitic induced mortalities of adult salmon has been noted in Alaska. Increased pre-spawn mortality of adult Chinook salmon in the Yukon River, Alaska has been linked to infection by a protozoan parasite, *Ichthyophonus* spp. (Kocan et al. 2003) and rising average water temperatures in the last thirty years appear to be associated with the increase of the disease and the increased pre-spawn mortality. This parasite has now been found in herring in Puget Sound (Jim Winton, USGS, personal communication), and there is a high probability that if it is not already in the Columbia Basin, it will be soon.

The most likely locations where such health problems could occur for adult salmonids in the Columbia River Basin due to increasing water temperatures and high fish densities, would be in fish ladders at Columbia River Basin dams and in tributary spawning streams during low flow periods in the summer and fall.

Biological Effects – Other Species

Changes in distribution and abundance of introduced and exotic species in mainstem reservoirs

Introduced species (especially invasive exotic species) can have a distinct advantage in competing with native species because they escape a large percentage of the pathogens and parasites from their native range and are slow to pick up new infections in their newly invaded range (Torchen and Mitchell 2004). There is convincing evidence that non-native fish species are continuing to increase in the Columbia Basin aquatic habitats and climate change is likely to further accelerate their expansion, often at the expense of native species.

There is evidence that the resident fish assemblages in shallow nearshore habitats of Columbia River reservoirs are changing at a fairly rapid rate. In 1995, Barfoot et al. (2002) replicated an earlier 1984-85 study (Palmer et al. 1986) and found that relative fish species composition was very similar in 1984 and 1985, but was very different in 1995. During 1984-85, four native taxa (chiselmouth, northern pikeminnow, suckers, and sand rollers) dominated the catch (90%) and introduced species comprised 1.3%. In 1995, the same four native taxa comprised only 37.7% of the fish fauna and 33.9% were introduced taxa (primarily sunfishes and yellow perch), with the remaining 28% consisting of sculpin, peamouth, and several species of minnows. One of the primary explanations for this shift in composition was that the impoundments have created sloughs and backwater habitats where water exchange is very low and summer water temperatures are often several degrees warmer than the nearby main-channel habitats (Gadomski and Barfoot, 1998). These higher late summer temperatures have most likely caused native taxa to shift habitat use out of backwaters, while introduced warm-water taxa have moved into these habitats and remained there (Barfoot et al. 2002). With predicted increases in water temperatures, the expansion of introduced and exotic species into these backwater and shallow water habitats will most likely continue.

Concurrent with these temperature increases in backwater and shallow water habitats of mainstem reservoirs, introduced warm-water and cool-water piscivorous fishes, such as centrarchids and percids are expanding their distribution and numbers (Poe et al. 1994). In some areas of the mainstem Columbia River smallmouth bass have been documented to prey selectively on wild fall Chinook subyearlings (Tabor et al. 1993). Any future increases in temperature will certainly favor further expansion of warm-water piscivores like largemouth bass and channel catfish which are already present in mainstem reservoirs (Poe et al. 1991).

The rapid increase in the introduced American shad in the Columbia River coincides with the 1977 climatic regime shift in the north Pacific Ocean and the Pacific Northwest region (Beamish et al., 1999; Petersen and Kitchell, 2001; Petersen et al. 2003). It is known that shad spawn in a variety of habitats and the shad juveniles prefer rearing in warm water temperatures between 19°C and 25°C (Ross et al. 1997). Larval and juvenile shad are suspected to have a potentially significant impact in reducing the abundance and size of *Daphnia* spp. in two lower Columbia River reservoirs during summer (Haskell et al. 2006). This could have an impact of reducing the food resources for subyearling Chinook which prefer *Daphnia* spp. and rear in these reservoirs (Rondorf et al. 1990). Temperature increases and flow decreases in summer may also alter food web dynamics by causing zooplankton abundance, primarily cladocerans and copepods, to peak earlier in summer. This could reduce the availability of *Daphnia*, currently an important food source for emigrating subyearling fall Chinook, by enabling the juvenile shad to deplete this important food source prior to the entry of subyearling Chinook salmon into the mainstem reservoirs (Haskell et al. 2006). Future increases in water temperature will likely continue the expansion of shad in the Columbia River Basin. Research is needed to examine the potential interactions between larval, juvenile and adult shad and juvenile salmonids (Petersen et al. 2003).

White Sturgeon and Pacific Lamprey

While the thermal tolerance range of adult white sturgeon, *Acipenser transmontanus*, may be quite broad, several studies have documented some temperature requirements for spawning and egg incubation and survival. Spawning of the Columbia River white sturgeon typically occurs between 10^{o} and 18^{o} C with the peak spawning from 13^{o} to 15^{o} C (Parsley et al. 1993) usually in about June. Egg mortality increases when incubation reaches 18^{o} C and total egg mortality occurs at 20^{o} C (Wang et al. 1985). The Kootenai River white sturgeon also spawn in May or June; however, water temperatures are much cooler, about 8^{o} to 9^{o} C, and spawning ceases by 12^{o} C (Paragamian et al. 1995). Eggs incubated at cooler than optimal temperatures develop normally but take longer to hatch (Wang et al. 1985). The other important factors that may be needed for successful white sturgeon recruitment is high water velocities that now occur primarily in tailrace areas below hydroelectric dams in the Columbia River Basin (Parsley et al. 2002) and submergible riparian rearing habitat (Coutant 2004). Under future scenarios of warming water temperatures and reduced summer flows there is a likely possibility that the white sturgeon may be stimulated to spawn earlier than the May – June period. This may actually be advantageous for white sturgeon for both egg incubation/survival as well as flow/velocity requirements for successful recruitment. However, if white sturgeon do not spawn earlier due to warming water temperatures, the predicted lower summer flows will decrease or extinguish the already almost non-existent recruitment in the Columbia River Basin.

Pacific lamprey, *Lampretra tridentate,* populations have declined significantly in the Columbia River Basin since the 1940s (Close et al. 1995). However, there has been very little research conducted to understand their life history, spawning and rearing habitat requirements, and factors limiting their production in the Columbia River Basin. In a laboratory study to determine the thermal requirements of early life stage lamprey (Meeuwig et al. 2005) with 22 ^{o}C determined to be the upper limit for successful survival of egg incubation and larval survival (though survival of larval lamprey was significantly less at 22^{0} C than 3 lower temperatures).

One recent lamprey passage study done by Vella et al. (1999 a and 1999b) has revealed that up to 80% of radio-tagged lampreys have failed to pass Bonneville Dam. The cause for this apparent passage failure has yet to be determined and potential reasons could be behavioral disorientation, swim performance limitations, physiological stress/exhaustion, depletion of energy reserves, thermal stress, or a combination of any of these factors. A study was recently conducted to estimate the oxygen consumption of lampreys swimming at several different speeds and three different temperatures (10, 15, and 20 ^{o}C) (Mesa and Bayer USGS unpublished data). Results indicated that lampreys had difficulty swimming at the higher water velocities and consumed greater rates of oxygen at the highest temperature. Future rising water temperatures may require lampreys to use higher reserves of energy and lead to exhaustion while attempting to pass hydroelectric dams, further pushing Pacific lamprey towards extinction in the Columbia River Basin.

Effects in the Estuary

The literature on effects of climate change on northeast Pacific estuarine habitat and ecosystems is limited - most of the papers on effects of climate change in estuaries focus on coastal plain estuaries on the Atlantic coasts of North America and Europe. Major estuary programs on the west coast such as the CALFED Delta Program have only recently started to focus on the problem (CALFED, 2003). We therefore found little data that relates specifically to the lower Columbia River and estuary. For example the major review paper by Scavia et al. (2002) does not mention the lower Columbia River and estuary. Further, the extensive literature on effects of climate change on salmonids has tended to focus on either freshwater or marine effects (see references elsewhere in this ISAB report). For this reason we had to make inferences about climate change effects from the existing general ecological and fisheries data on the lower Columbia River and estuary.

In the both the vertical and horizontal plane, an estuary is a complex transitional zone without sharp boundaries between freshwater and marine habitats. Any conclusions about possible climate change effects within an estuary must therefore also consider changes in the latter two habitats – freshwater effects propagate into the estuary from the river and marine effects from the ocean. An estuary may be highly stratified vertically, with freshwater on the surface and salt water near the bottom, and therefore changes in water properties and biota with depth also need be considered.

Possible Changes in Oceanographic and Hydrological Conditions in the Estuary

Changes in Columbia River freshwater flow due to climate are expected to propagate through to the lower Columbia River and estuary but will less than those caused by construction of the hydrosystem (Fig. 11). Current long-range forecasts suggest there will be higher average Columbia River flows in winter and early spring flows and less snowmelt in summer in future years because of warmer temperatures, more precipitation as rain, and less snow storage. Late spring-autumn flows could be reduced and winter flows high but undependable (more floods). Reduced spring and summer flows could result in further attenuation of an already decreased flooding regime which has changed the amount of time specific elevations are submerged relative to natural conditions. (Fig. 15).

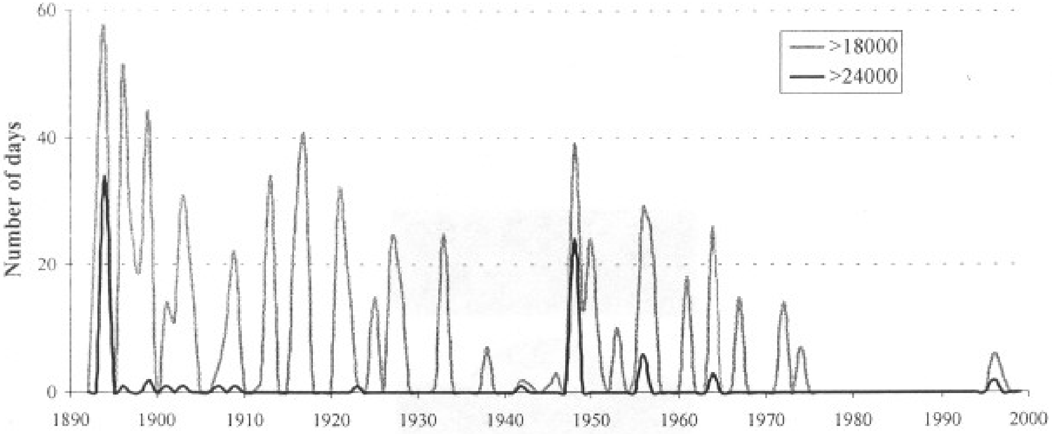


Figure 15. The incidence of flows above 18,000 m^3s^{-1} (the pre-1900 estimated bankfull flow level) and above 24,000 m^3s^{-1} (the present bankfull flow level). The present bankfull flow level has only been exceeded in four years since 1948 (Fig 28 from Bottom et al. 2005).

The best measure of total main stem freshwater input at the head of the estuary is the Columbia River flow at Beaver (river km 85), although there are some major rivers below this point (e.g., Grays River). At this location the pre dam (1892-1902) average estimated observed annual flow was 8300 m^3s^{-1} compared to 6960 m^3s^{-1} for the 1892-1999 period (Bottom et al. 2005). It is extremely difficult to separate climate, flow regulation, and water-withdrawal effects on the freshwater flow into the lower Columbia River and estuary. However changes in flow or water quality upstream will be transported to the estuary. Thus, any warming in the tributaries and reservoirs may result in warming of the estuary.

Temperatures in the estuary are significantly influenced by river and reservoir surface water because temperatures in the upper estuary and tidal freshwater are higher relative to reaches closer to the ocean. Only a few relatively long term data sets on temperature are available for the estuary and lower river. For example, in August 1981 mean surface temperature was about 14^o C at river mile 5 compared to about 22^o C at river mile 50 (Fig. 16). Recent water temperature at Warrendale, Oregon (river mile 141) in the tidal freshwater part of the river showed numerous dates when surface temperature exceeded 20^o C (Fig 17). Temperatures in the estuary are also influenced by tidal entrainment of ocean water that is often cool during the summer upwelling periods.

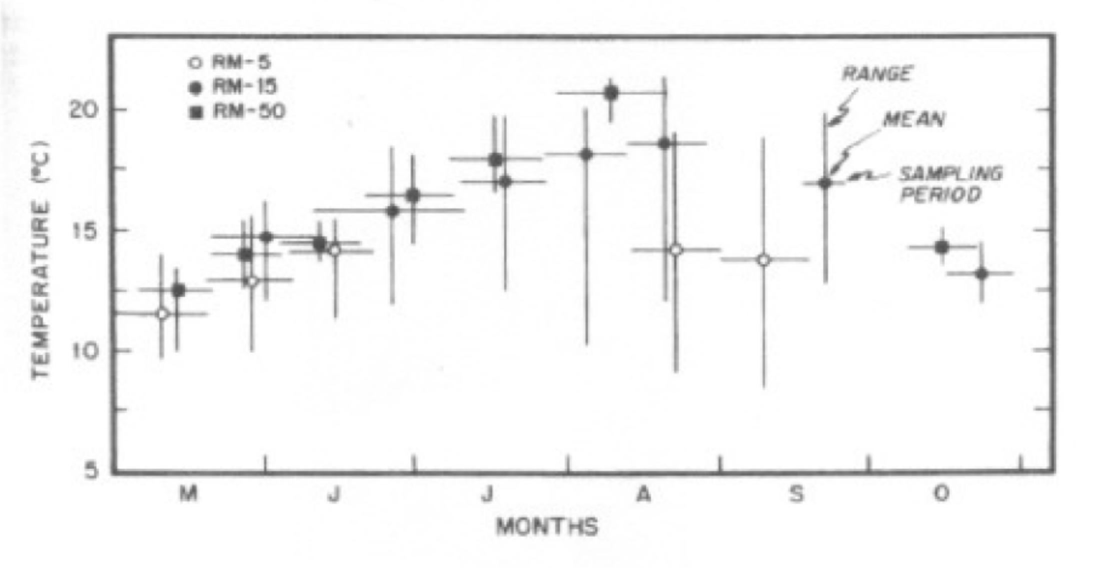


Figure 16. Mean temperatures and range measured at three mid-depth (6-9 m) stations at river mile 5, 15, and 50 in the Columbia River estuary, 1981. (Fig 3 from Bottom and Jones 1990).

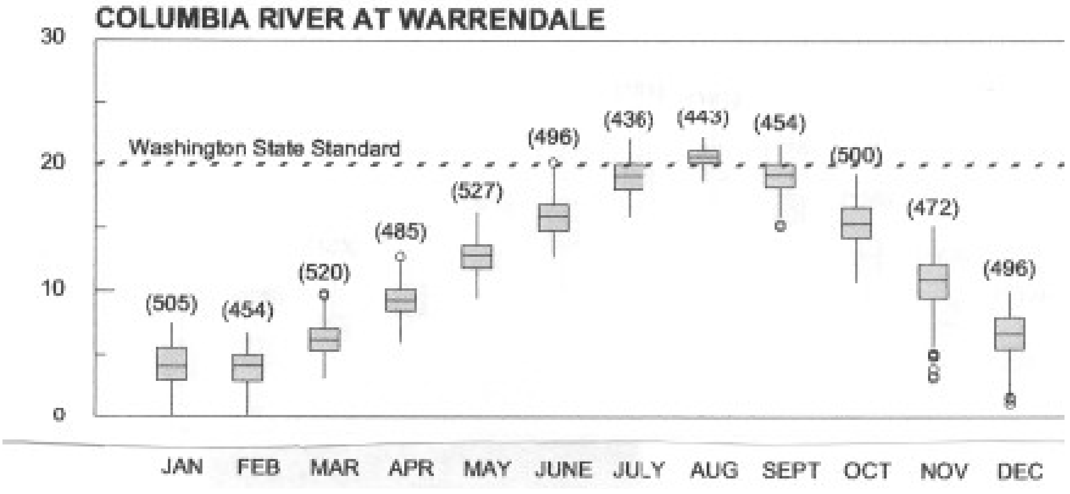


Figure 17. Median surface temperatures (middle line in box plot) at Warrendale (river mile 141) in the Columbia River based on measurements made between 1975 and 1992. The Washington State temperature standard is shown as a dashed line. Numbers beside boxes indicate number of observations (from Fuhrer et al. 1996).

Key habitats in the lower Columbia River and estuary for fall Chinook and chum salmon, such as wetland platforms, mud flats, and floodplains, are generated and maintained by sediments supplied from upriver tributaries (especially the Willamette River) and moved downstream in suspension. Suspended sediment increases downstream (e.g., 5 mg l^{-1} at Warrendale OR to 9 mg l^{-1} at Beaver OR (Fuhrer et al. 1996). Because some of the sediment load arises from re-suspension by bottom currents, decreases or increases in river flows from climate change could be influential. As well the effects of climate cycles, such as the PDO, are amplified in the sediment flow – increased river flow during cool wet La Niña years resulted in higher sediment loads from eastern subbasins (Bottom et al. 2005). The distinct responses of sand transport (limited by transport capacity and, therefore, changes in flow) and fine sediment transport (limited by supply and, therefore, land use) suggest that other factors besides flow regulation, irrigation depletion and climate need to be considered with regard to sediment transport in the lower Columbia River and estuary. A combination of analysis of hindcasts and landscape modeling will be needed to fully understand the historical changes in sediment transport (Naik and Jay 2005) but sediment input to the estuary has declined due to the altered hydrograph (Bottom et al. 2006)

The distance that salt water moves upstream under the freshwater into the lower Columbia River and estuary is a complex function of tides and river flow. At present, during spring, when both tides and river flows are at their seasonal maxima, the salt wedge penetrates approximately 16 km into the estuary (Fig. 18). With reduced spring flows, this distance would be increased. Warming of the ocean at the mouth of the river could result in reduced strength of the salt wedge, since density differences between salt and freshwater are the main drivers for this phenomenon. Warmer ocean water might penetrate shorter distances upstream under the freshwater because it is less dense.

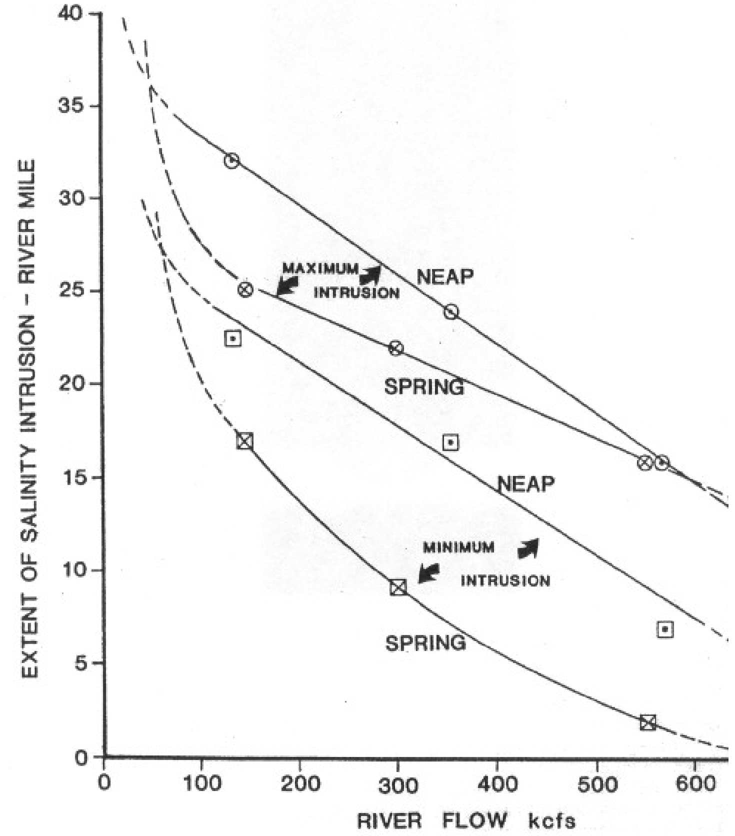


Figure 18. Maximum (end of flood tide) and minimum (end of ebb tide) salinity intrusion distance in the Columbia River estuary, based on 1980 bathymetric conditions (Fig 32 in Bottom et al. 2005 from Jay 1984)

Assuming no future changes in management of the hydrosystem, decreased spring and summer flows owing to climate change could result in shallowing of some channels in the lower Columbia River and estuary, and this could imply increased dredging to keep navigational channels open (see ISAB 2000). Increased fall and winter flows could offset this effect but only in these seasons and dredging would still be required.

Sea level rise and possible degradation of habitats created by sediment deposition owing to increased wave actions (storms) are also climate change impacts that could change estuarine ecosystems. The most recent estimates of sea level rise at the end of the 21st century range between 0.18 and 0.59 m for the world ocean (IPCC 2007) – we found no estimates available for the northeast Pacific specifically. Sea level rise could be particularly important at the mouth of the river where the Columbia River littoral cell, generated by wave and current action, move sediments north and south and generates sandy beach habitats (Mitchell 2001). Data on effects of wind-generated wave action in the estuary proper are not available but wave cut terraces along the shoreline of the estuary could become more pronounced with increased storms and could affect the success of restoration projects using dredged sand (see below).

Hydraulic models have shown that water mass residency in the lower Columbia River and estuary was inversely correlated with stream flow but the relationship was complex (Sommerfield 1999 cited in Bottom et al. 2005). Decreased spring flow could result in increased residency time and the converse might be expected for increased winter flow. The flushing or residency time is an important descriptor of the behavior of water parcels in an estuary and is particularly important for distribution of food web materials and water quality since it determines how long particles are retained in the estuary (e.g., detritus important in the food web, trapping of pollutants). The models showed that residency in the lower estuary can vary from 10 to 60 h, depending on flow. Residence time for suspended particulate material for the north and south channels together suggests that sediment storage is short (less than 14 d) during the spring freshet—most of the suspended particulate material brought into the estuary is exported at the latest on the next spring tide (Faini et al 2001). However owing to channelization and changes in flow the embayments off the south channel are now more effective sediment traps, judging from changes in marsh vegetation at Russian Island in Cathlamet Bay (Bottom et al 2006)

Biological Responses

In the following, we focus on responses by ocean-type Chinook salmon and their supporting ecosystem, given that this species is known to rely on estuarine conditions (Healey 1982; Bottom et al 2005). Where necessary, we extrapolate to other species, and, recognizing that all salmonids must transit the estuary as juveniles and returning adults, we also discuss other species of the salmon community.

Temperature effects

Temperature is widely recognized as a controlling factor for growth and survival in aquatic habitats and is also a key parameter related to climate change. There are few data that pertain directly to estuaries on this topic. However, numerous water quality criteria documents deal with this topic, and salmonids are usually listed as a sensitive group of organisms.

Most of the physiological research on the temperature tolerance of salmonids has been done in freshwater or ocean conditions (see elsewhere in this report and Young et al. 2006). The physiological implications for juvenile salmonids moving from a cold river to a warm upper estuary and then to a cool or possibly warmer ocean, as might be experienced with climate change, has not been researched. Returning adult salmonids are adapted to a different situation, experiencing cool temperatures in the coastal ocean, traveling through an often-warmer estuary and river, then to cooler spawning grounds. Climate change could modify this gradient in any of the above habitats. Returning salmon holding in estuaries while waiting for cool runoff conditions in their natal river can suffer stress and disease, as observed for sockeye in Alberni Inlet, BC (Johnson et al. 1996) during a regional warming trend or the die off of thousands of salmon in the Klamath River in 2002 (California Department of Fish and Game 2003).

Both juvenile and adult salmon suffer direct lethal heat shock or sublethal effects if they are subjected to temperatures above approximately 20° C, but it is very difficult to generalize for estuarine habitats because of the strong interaction with salinity (Clarke et al. 1981) and oxygen (Davis 1975; Marchand et al. 2002). Temperatures above 20° C can be achieved in certain estuaries where heated effluents (e.g., cooling water for power plants, Marchand et al. 2002). However, there are species specific differences in temperature tolerance (see below). Sublethal effects are also possible. Takami (1998) found that water temperatures > 16° C reduced the osmoregulatory ability of white spotted char, but low temperatures (< 4° C) did not.

Temperature mediates numerous indirect effects on salmonids, especially at the juvenile stage. Temperature controls rate processes such as growth and metabolism and hence strongly influences the food demand in the estuary, as found for Chinook by MacFarlane and Norton (2002) in the Sacramento River estuary-San Francisco Bay area. However, as mentioned, salinity is a key interactive factor that is usually not considered in ecophysiological models.

Knowledge of the extent to which the behavior of various Chinook populations in the estuary are genetically programmed, as opposed to environmentally responsive and plastic is poor. Perhaps the recent paper by Brannon et al. (2004) is relevant. They surmise that Chinook life history genetics are conditioned by temperature (i.e., life history types are arrayed on a temperature continuum). As well, as found by Crozier and Zabel (2006) in freshwater, the Chinook salmon response to climate change may be population specific.

Alteration of fry and smolt arrival and residency in the estuary

Rich (1920, cited in Bottom et al. 2005) found at least six specific life history patterns for wild Chinook in the pre-development lower Columbia River and estuary. These were variants of the broad life history categories commonly known as stream-type and ocean-type (Healey 1991). Contemporary timing and relative abundance data indicate this has been narrowed to three patterns (Bottom et al 2005), with a possible fourth (reservoir type Chinook, see above) that is undocumented in the estuary (ISAB 2006). At present, fry and yearling fish peak in abundance in early April and fingerling catches peak in early July (Fig. 19). Hatchery smolts are now the dominant forms with complex but narrow arrival times into the estuary.

River flow is one of the dominant factors influencing arrival time and residency in the estuary, especially for hatchery smolts which tend to move through the estuary more quickly than wild fish (Bottom et al. 2005). Therefore it is likely that, in the absence of future changes in hydrosystem operations, changes in discharge owing to climate change will modify the above-mentioned patterns of estuary usage.

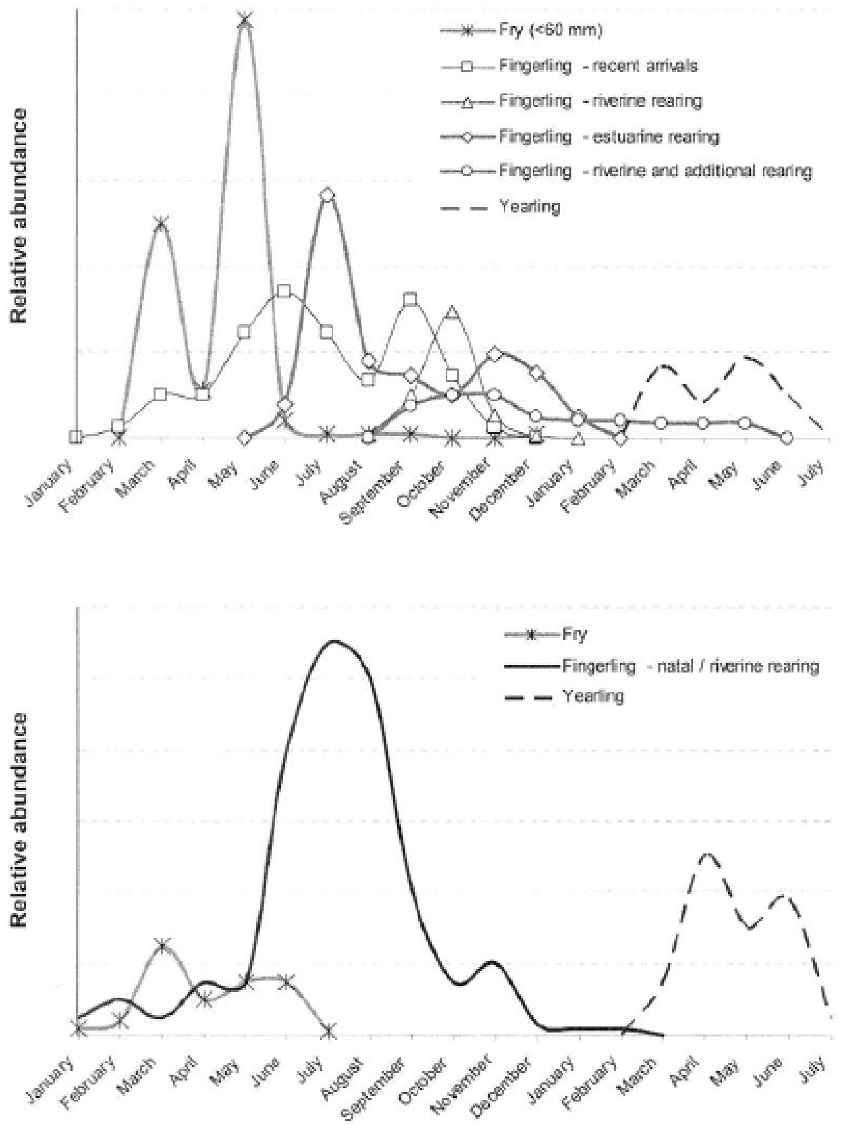


Figure 19. Historical and contemporary early life histories for one broodyear of Chinook salmon in the Columbia River estuary. Historical timing and relative abundance (top panel) based on historical sampling throughout the lower estuary (Rich 1920). Contemporary timing and relative abundance (bottom panel) derived from Dawley et al. (1985) sampling at Jones Beach (river mile 46) (Fig 79 from Bottom et al 2005).

Alteration in the fish community

Water temperature increases in the estuary may favor the survival of non-salmonid fish species in the estuary, some of which may prey or compete with juvenile salmonids. Numerically, non-salmonids are more abundant than salmonids in the intertidal habitats of the lower Columbia River and estuary (McCabe et al. 1983). Monaco et al. (1992) included the lower Columbia River and estuary in what they termed the "Northern Riverine Group" when classifying estuaries on the northwest coast based on fish species. This group was strongly associated with salmonids and cool water requirements. Abundant endemic species, such as staghorn sculpin (*Leptocottus armatus*), found in the estuary (McCabe et al. 1983; Bottom and Jones 1990) are not now known as major predators in the lower Columbia River and estuary on juvenile salmonids. This situation could change if warmer temperatures increased consumption rates of piscivores, as found by Footen and Tabor (2001) in Lake Washington in a study of endemic and non-indigenous fish predators and juvenile salmonids.[1] If cool water species like northern anchovy decline in the lower Columbia River and estuary, more predation could occur on juvenile salmonids by Caspian terns that nest in the estuary.

Numerous warm adapted fish species, including several non-indigenous species normally found in freshwater (e.g., carp (*Cyprinus carpio*), yellow perch (*Perca flavescens*)) have also been reported from the estuary (e.g., McCabe et al. 1983; Weitkamp 1994) and might expand their populations if conditions allowed (e.g., warmer water, expansion of freshwater habitats). Some of these species, and possibly those currently found further upriver (e.g., northern pike *Esox lucius*) could encroach into the lower Columbia River and estuary with higher flows. The ISAB (2000) noted that American shad (*Alosa sapidissima*) was by far the most abundant non-indigenous fish species in the lower Columbia River and estuary. The effects of climate change on the population dynamics of this species are not known.

Effect of flooding on available rearing space

The model developed by Bottom et al. (2005) showed that there was a correlation between stream flow and habitat availability for fish as preferred habitat is submerged for longer periods during higher flow. The relationships were more complex when depth criterion and combined depth-velocity criteria were used. Sea level rise owing to climate change would add to the complexity. According to model forecasts, reduced stream flow in spring would reduce habitat opportunity. Although not investigated with the model, the relationship implies that more habitat would be available for rearing in the estuary in fall and winter, for example, for reservoir-type Chinook moving seaward from the reservoirs. Sea level rise in the Columbia River due to climate change is expected to propagate upstream into the lower Columbia River and estuary, but will be substantially less than the May-June-July water level decreases caused by construction and operation of the hydrosystem.

Possible changes in trophic dynamics, food webs, and connectivity

Tidal flows and freshets are hydraulic forces that strongly influence primary production of vascular plants, benthic algae, and phytoplankton and also distribute the generated carbon to bacteria for heterotrophy, generating detritus and to the secondary consumers

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[1] www.ci.seattle.wa.us/salmon/docs/workshop/footen.pdf (accessed Oct 17, 06).

(invertebrates) which in turn are eaten by juvenile salmonids rearing in the estuary. However, this food web structure of the lower Columbia River and estuary has been altered by reservoir construction which altered production processes, modified flow, and changed seasonal patterns of flooding.

Decreased flows in spring and summer could result in a reduction of upriver detritus source for the estuary, possibly moving the estuary closer to the historical situation. An important set of food web pathways leading to juvenile salmonids that feed in the estuary is thought to be dominated by heterotrophic processes involving detritus and bacteria originating from vascular plants and phytoplankton (Sherwood et al. 1990). Production of phytoplankton in the large lakes created by dams is now a major source of this detritus, relative to the pre-dam condition.

As explained above, the salt wedge may penetrate further upriver in spring-early summer if these flows are reduced owing to climate change. The landward head of the salt wedge is characterized by a turbulent region known as the estuary turbidity maximum, an ecotone of high bacterial production by specific microbes (Crump et al. 1999) and concentrations of fish food organisms such as harpacticoid copepods (Simenstad et al. 1994). Changes in the distribution of the salt wedge will influence the location of the estuary turbidity maximum, but it is difficult to forecast the ecological effects that might propagate to higher trophic levels such as juvenile salmon.

The hydrosystem and diking have caused major changes in the flooding regime in the lower Columbia River and estuary, and climate change will modify it further. Overbank flooding from the spring freshet is widely recognized as a mechanism for distributing detritus from vascular plants in the horizontal plane of the estuary (e.g., sedges (*Carex lyngbyei*)) (Macdonald 1984). However, because of hydrosystem operations, modern flows required to generate the phenomena (24,000 m^3s^{-1}) are extremely rare now. Overbank flow is rare now even during cold wet PDO phases and was totally absent during the last PDO warm phase (1977-1995) (Bottom et al. 2005, Fig. 15). Depending on hydrosystem operations, increased winter freshets coupled with sea level rise could increase the occurrence of overbank flow in winter. However, overbank flow may become even less frequent during late spring and summer if climate change further reduces natural runoff at this time of year. Overbank flow is not expected to increase with higher discharge in autumn and if it did this would result in distribution of detritus at the wrong season for fish food invertebrates to utilize it for growth and reproduction.

Changes in sediment supply from flows modified by climate change could modify the integrity of intertidal habitats in the lower Columbia River and estuary – these account for 40% of the area of the estuary (Wissmar and Simenstad 1998), especially as the sediment supply to the lower Columbia River and estuary has already been drastically reduced by the hydrosystem. Mud flats and tidal flat areas in the lower estuary are important detrital producers. For example, Baker Bay, Trestle Bay, Youngs Bay, and Cathlamet Bay produced 82% of the total benthic algal production in the estuary. Net annual primary production by emergent vascular plants in Youngs Bay was highest in the low marshes of the area (about 1000 gC $m^{-2}y^{-1}$) (Small et al. 1990).

Effects on Estuarine Restoration Projects

Estuary restoration projects that have been planned and built with contemporary hydraulic and flow conditions in the lower Columbia River and estuary may need to be re-engineered if climate change reduces flow in spring and summer. Dike breaching projects, for example, may need to modify the elevation of ports for water inflow or control to account for heavier wave action, higher flows, and sea level rise. Culvert repositioning might also be required. Stronger wave action, however, could improve some problematic restoration projects such as dredged sand islands where bird predation on salmon smolts is severe (Collis et al. 2002). Bird nesting habitat might be scoured and reduced if flood currents become stronger in winter.

Effects in the Ocean

Scientific evidence strongly suggests that global climate change is already altering marine ecosystems from the tropics to polar seas (McPhee 1998; Levitus et al. 2000; Overland and Stabeno 2004; Whitney 2006a; and IPCC 2007). In the Pacific Northwest global climate changes are predicted to influence both freshwater and marine ecosystems. Changes in the ocean associated with warming will affect salmonids and their ecosystems, both directly and indirectly. Physical changes associated with warming include: increases in ocean temperature, increased stratification of the water column, and changes in the intensity and timing of coastal upwelling. These changes in climate forcing will alter both primary and secondary productivity and the structure of marine communities, and in turn, the growth, productivity, survival and migrations of salmonids.

Eastern boundary currents along the west coast of North America are enriched by wind-driven coastal upwelling and mixing processes resulting in productive ecosystems that support diverse marine life and major fisheries. These coastal systems are also inherently highly variable in both space and time, with changes occurring on scales of days and weeks, seasonally, interannually and interdecadally. Timing and intensity of upwelling varies greatly within and among years, El Niño-Southern Oscillation (ENSO) events occur on average every 2 to 7 years, and 20th century regimes in ocean climate and marine ecosystems, key aspects of which are reflected in the Pacific Decadal Oscillation (PDO), have lasted 20-30 years. On time scales of millennia, large natural variations in the productivity of salmon stocks have occurred over the past 3000 years in Alaska (Finney et al. 2000) and over 700 years in the Columbia River (Chatters et al. 1991, 1995). These high and low frequencies of natural variability in physical forcing and ecosystems confound detection of long-term trends in ocean temperatures, ecosystem properties, and other factors.

Climate Variability

Here we explore factors that are known to affect the climate of the Pacific Northwest. These include Aleutian Low variability, El Niño events, and PDO phases. These are all possible analogs for future impacts of global warming in the North Pacific and Pacific Northwest.

Climate conditions are clearly important in the fluctuations of abundances of salmon because climate is a key part of salmon habitat at every stage of their lives. In the past, studies have shown a strong correlation between multi-decadal climate cycles and trends in the population abundances of salmon, with responses varying across broad geographic ranges (Beamish and Bouillon 1993, Hare and Francis 1995, Mantua et al. 1997; Hare et al. 1999; Tolimieri and Levin 2004; Zabel et al. 2005; Mueter et al. 2002). Regional aspects of marine and freshwater habitat important for Pacific Northwest salmon are frequently influenced by ENSO events and phases of the PDO. A particularly important pathway for ENSO and PDO variations to impact Pacific Northwest salmon habitats is via their influence on the characteristics of the cool season Aleutian Low atmospheric pressure cell.

Aleutian Low and Subtropical High pressure Cells

Beginning about mid-October in each year a semi-permanent, low-pressure cell, commonly called the *Aleutian Low*[2], intensifies and migrates southeastward over the Aleutian Islands and Gulf of Alaska. Surface winds blow in a counterclockwise circulation around the Aleutian Low. Further south, winds blow in a clockwise circulation around a semi-permanent center of subtropical high pressure typically centered offshore southern California. Prominent cool-season climate changes over the North Pacific Ocean and western North America are associated with fluctuations in the strength and location of the atmosphere's Aleutian Low pressure cell and associated position of the Pacific storm track (Fig. 20). The weak Aleutian Low circulation pattern typically brings a reduction in the poleward alongshore winds that tend to warm and stratify the coastal waters of the NE Pacific such that by the end of a weak Aleutian Low winter coastal ocean temperatures are cooler than average and the upper ocean is weakly stratified. In contrast, winters with an intense Aleutian Low have enhanced poleward winds along the Pacific coast, and this circulation pattern causes enhanced upwelling in the center of the Alaskan Gyre, increased wind mixing of surface waters and onshore transport of offshore waters in Alaska such that by spring time coastal waters of the NE Pacific are anomalously warm, surface mixed layers are anomalously deep. These atmospheric circulation patterns drive surface currents, with a strong low intensifying the Alaskan Current, and a weak low and strong subtropical high pressure cell intensifying the California Current (Fig. 20).

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[2] Although the Aleutian Low dominates the winter (seasonally averaged) climate of the North Pacific, it is a statistical feature of the winter circulation in that its existence relies on the frequent development of eastward moving winter storms along a more-or-less regular path. The individual winter cyclones have a typical lifetime of one to a few days.

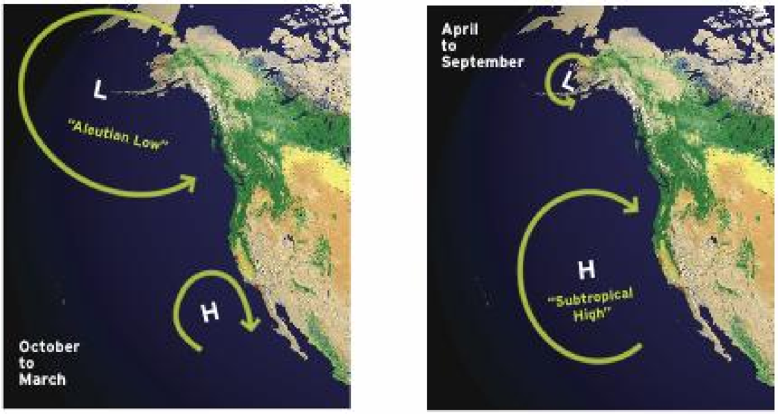

Figure 20. PRESSURES and CURRENTS: From October through March the atmospheric sea level pressure field is dominated by low pressure and frequent winter storms (cyclones) over the North Pacific, giving rise to the climatological feature known as the Aleutian Low pressure cell. As indicated by the yellow curved arrows, the circulation around the Aleutian Low brings surface winds onshore and from the southwest into the Columbia River Basin and greater Pacific Northwest region. From April through September the Aleutian Low is substantially weaker and retreats northward, and the dominant feature in the Northeast Pacific is a subtropical high pressure cell that favors north-to-south alongshore winds along the west coast of the continental United States that cause coastal upwelling of cold nutrient waters into the California Current System. The West Wind drift carries subarctic waters into the coastal waters of the North Pacific, while copious freshwater runoff from the coast range of British Columbia and Alaska give rise to the Alaska Coastal Current. (Figure reproduced from the 2007 Sound Science report).

The same Aleutian Low circulation changes that alter the upper ocean properties of the NE Pacific also have important impacts on precipitation, temperature, and snow packs in the Pacific Northwest region. Weak Aleutian Low winters typically have an active storm track over the Pacific Northwest that bring relatively cold and frequent storms, heavy precipitation and plentiful snowfall on the west slopes of the mountains. In contrast, periods with a strong Aleutian Low typically bring a split storm track that diverts storms to both the north and south of the Pacific Northwest region, which results in relatively warm and infrequent storms, and reduced precipitation and snowfall throughout the region.

These climatic changes over land then carry over into late spring and summer streamflows in what is typically a very strong seasonal snow melt pulse across the region's major watersheds. Table 3 summarizes some of the key habitat changes associated with fluctuations in the intensity of the cool season Aleutian Low[3].

Table 3: Summary of the influence of Aleutian Low variations on regional aspects of Pacific Northwest salmon habitat. Note that strong Aleutian Low winters are favored during El Niño and warm phase PDO periods, while weak Aleutian Low winters are favored during La Niña and cool phase PDO periods.

	Regional Precipitation	Regional Temperature	Regional snow pack and snow melt runoff	Coastal ocean water temperatures and stratification in winter and spring
Weak Aleutian Low	High	Low	High	Low
Strong Aleutian Low	Low	High	Low	High

El Niño/Southern Oscillation and Pacific Decadal Oscillation

Both ENSO and PDO are patterns of Pacific climate variability that include changes in sea and air temperatures, winds, and precipitation. ENSO is a natural part of climate that spontaneously arises from interactions between tropical trade winds and ocean surface temperatures and currents near the equator in the Pacific. Because of long-distance atmospheric and oceanic teleconnections, ENSO is a prominent source of cool season Aleutian Low and Pacific Northwest climate variability at year-to-year time scales. During El Niño events the Aleutian Low tends to be intense and shifts to the southeast, and these changes result in relatively dry and mild fall-winter periods in the Pacific Northwest region, along with warm upper ocean temperatures throughout the northeast Pacific Ocean and along the entire west coast of the Americas that persist from spring into summer. In contrast, the Aleutian Low tends to be weak and displaced to the northwest during La Niña events, and these changes result in relatively cool and stormy fall-winter periods for the Pacific Northwest region, along with relatively cool upper ocean temperatures throughout the northeast Pacific Ocean and along the entire west coast of the Americas that persist from spring into summer (Mantua et al. 1997).

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[3] At time scales shorter than a few months, prominent changes in the Aleutian Low and storm track arise from instabilities contained within the chaotic flow of the atmosphere, and these processes lead to a fundamental limit in weather prediction of about 2 weeks. In practice, aspects of current *weather forecasts* have demonstrated skill at lead-times of up to 5 to 10 days in the best case scenarios. At interannual to interdecadal time scales there are two ocean-atmosphere climate processes especially prominent in Aleutian Low and Pacific Northwest climate variability: El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation.

Some of the broad-scale effects of PDO phases are summarized in Table 4, showing how physical and biological indicators vary with cool and warm PDO conditions.

Table 4. Summary of the manner in which the sign of the PDO influences broad–scale and local physical ocean condition indicators as well as biological indicators.

	Cool PDO	Warm PDO
Broad–scale ocean indicators		
Pacific Decadal Oscillation values	negative	positive
Multivariate ENSO Index values	negative	positive
Local physical indicators		
Upwelling	positive in winter-spring	negative in winter-spring
Physical spring transition[a]	may not be related to PDO	
Sea surface temperatures	cold	warm
Continental shelf water type	cold and salty	warm and fresh
Local and regional biological indicators		
Copepod species richness	low	high
Northern copepod biomass	positive anomaly	negative anomaly
Southern copepod biomass	negative anomaly	positive anomaly
Euphausiid egg abundance in shelf water	usually high	usually low
Biological spring transition	early	late
Trawl surveys		
Coho abundance	high	low
Chinook abundance	high	low
Coho survival[b]	high	low
Developing indicators		
Snake River Chinook SARs[c]	high	low
Forage fish abundances	many	few
Pacific hake abundances	few	many

(http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm)

a (Logerwell et al. 2003)

b (OPIH) Oregon Production Index, Hatchery

c Smolt to adult returns (see Scheurell and Williams 2005)

At time scales of one to a few decades, PDO impacts are manifest as ENSO-like changes in the spatial patterns of ocean temperatures and Pacific Northwest weather. Warm phases of PDO are linked with El Niño-like climate anomalies, including periods having an intense cool season Aleutian Low. Likewise, cool phases of PDO are linked with La Niña like climate anomalies that include periods with a weak cool season Aleutian Low. The PDO was in its cool phase from about 1890 to 1925 and from 1945 to 1977. It was in its warm phase from 1925 to 1945 and from 1977 to at least the mid-to-late 1990's when there was a high frequency of warm ocean conditions in the coastal waters of northeast Pacific (Mantua et al. 1997; Minobe 1997). Coincident with a shift to a prevalence of tropical La Niña and cool phase PDO conditions, the California Current System (CCS) experienced a four-year period of cooler temperatures and increased coho and chinook production from 1999 through 2002. This cool productive era was followed by warmer and less productive period for west coast coho and chinook from 2003 through 2005 before cooling again from 2006 to present. This variability highlights the fact that there is large year-to-year variability in the physical and ecological state of the California Current System, and only part of this variability is clearly related to larger scale ENSO and PDO-related climate changes.

Differences in the temporal rhythms of ENSO and PDO are obvious: the lifetime of a typical ENSO event ranges from 6 to 18 months, and complete ENSO cycles typically have a 2 to 7 year period (Rasmussen and Carpenter 1982); by contrast, the energy in twentieth century PDO variations was concentrated at periods near 20 and 60 years, along with variations at periods less than a decade (Minobe 1999; Newman et al. 2003).

Additional key differences between ENSO and PDO lie in the state of current scientific understanding and demonstrated predictability of the two phenomena. Scientists are reasonably agreed that ENSO exists because of strong air-sea interactions that take place in the tropical Pacific. These interactions give rise to a deterministic set of climate events that are inherently predictable at lead times of at least a few seasons, and possibly up to two years. While ENSO has been extensively studied and is now routinely predicted at more than a dozen centers around the world, the causes for PDO variations are not currently known. Newman et al. (2003) show that key characteristics of the 20th Century's PDO SST pattern can be explained as a consequence of ENSO-related forcing and a strong tendency for multi-year persistence in extratropical ocean temperatures. If PDO variability is largely determined by the evolution of ENSO and relatively simple mechanisms that favor persistence in ocean temperatures, then PDO predictability is inherently limited by the same factors that limit ENSO predictability to perhaps two years into the future.

The relatively warm temperatures associated with the positive phase of the PDO and frequent tropical El Niño events during the1990-1998 period may represent a plausible scenario for the future since the predictions are for continued global warming (Meehl et al. 2001). A key caveat in this use of historic variability for analogs of future change is the prominent role that the persistently strong Aleutian Low pressure cell played in the warm era of 1990-1998. It is not clear that human-caused global warming will lead to similar persistence in the strength and location of the cool-season Aleutian Low and warm season subtropical high pressure patterns (and wind field) over the North Pacific and North America, but it is clear that the large-scale and regional scale surface winds will play a prominent role in structuring ocean habitat. We return to a more detailed discussion of the impacts of global warming on coastal upwelling winds later in this section.

Biological Impacts

Climate variability is linked to changes in ocean ecosystems, with physical changes forcing changes in primary and secondary productivity, forage fishes and predators that interact at different time and space scales. First we discuss some of the known impacts of ENSO and PDO in the Pacific Northwest, then discuss how possible future changes in stratification and upwelling might impact our coastal ecosystem.

The biological impacts of the 1982/82 and 1997/98 tropical El Niño events were particularly severe in the Pacific Northwest. Warm sea temperature, ineffective upwelling, and increased predation affected the distribution, survival and growth of many salmon stocks along the Pacific coast (Wooster and Flutharty 1985; Pearcy et al. 1985; Mantua et al. 1997). Five out of seven years in the late 1990s experienced El Niño-like events, as temperatures remained elevated (Trenberth and Hoar 1997). Perhaps El Niño events have been occurring more frequently than in the past (Rodbell et al. 1999), yet a recent review of climate models used in the IPCC assessments finds no consistent changes in the simulated behavior of ENSO in a warmer future (Collins 2005).

Shifts in the state of marine ecosystems, as reflected in the multi-decadal state of the PDO, are well documented in the Northeast Pacific Ocean (Table 4). From the 1920s to the 1990s a general inverse production pattern for Pacific salmon existed in the Pacific Northwest region vs. the northern subarctic Pacific (Francis and Hare 1994; Mantua et al. 1997; Hare et al. 1999). Warm conditions in the Alaska region resulting from a strong Aleutian Low and Alaskan Current usually have resulted in higher than average salmon catches, but lower catches in the California Current region. The regime shifted from a negative or cool phase to a semi-stable warm or positive phase in 1976/77 (Mantua et al. 1997). This warm phase, which included frequent tropical El Niño events, contributed to severe declines in the survival of Oregon coho salmon and lasted through the exceptionally strong 1997/98 El Niño event. During this period, large northern boreal and subarctic copepods decreased while smaller warm-water copepods dominated catches off in the California Current and off Canada (Mackas et al. 2001; Peterson and Schwing 2003). In addition, the peak of abundance of the dominant copepod, Neocalanus plumchrus, occurred about two months earlier in the subarctic Pacific along the "Line-P" transect west of Vancouver Island (Mackas 1998).

The PDO pattern shifted to its cool phase and the California Current intensified in the fall of 1998, and Pacific Northwest marine ecosystems returned to the more productive, cool state with increased productivity with predominance of large, lipid-rich, cold species of copepods. For the next four years (until the fall of 2002) salmon production in both regions was generally high and coho and Chinook salmon stocks in the Pacific Northwest rebounded. Survival of coho and Chinook salmon entering the coastal ocean in 1999-2001 improved substantially compared to the survivals of the preceding ten years. From 2003 to 2005 the PDO returned to a mostly positive, though variable state, and Pacific Northwest salmon production has shown signs of decline in concert with the return to warmer ocean conditions. On the other hand, La Niña-like conditions occurred during the 2006-07 winter, indicating more favorable conditions for salmon in the region.

In summary, if the regional impacts of global warming are expressed in El Niño-like or PDO-like ways, warmer waters due to global warming are likely to promote increased production of salmon in Alaskan waters, at least initially, provided primary and secondary production does not decline, while promoting decreased salmon production for salmon populations in the Pacific Northwest region (and throughout the California Current System). A key uncertainty here is how global warming will influence the characteristics of atmospheric surface pressure and wind fields over the North Pacific because of the prominent role that wind forcing plays in structuring the upper ocean.

Stratification

The density of water, which varies with salinity and temperature, affects stratification and mixing of surface waters. The thickness and stability of the surface mixed layer is a crucial factor in determining the effectiveness of nutrient inputs into the euphotic zone. Warm sea-surface temperatures and strong water column stratification impede wind mixing, which may reduce the availability of nutrients essential for the production of phytoplankton, the base of the ocean food web. On a global scale, upper ocean temperatures and increased stratification have already resulted in reduced net primary productivity since 1997. These trends are documented by Behrenfeld et al. (2006; Fig. 21) who show that ocean productivity is closely related to the Multivariate ENSO index (MEI) and changes in ocean stratification.

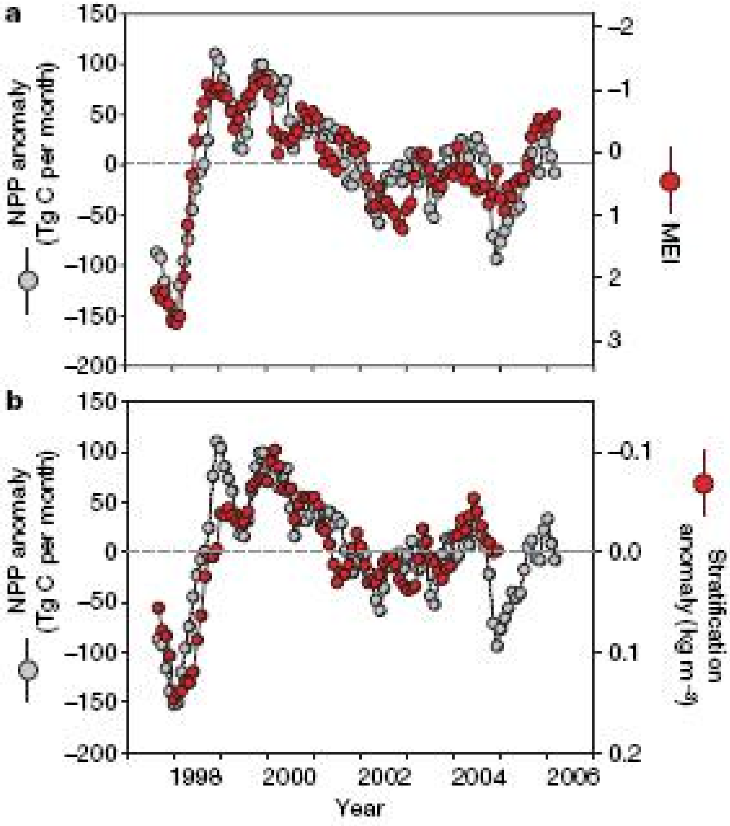

Figure 21. Ocean productivity is closely coupled to climate variability. **a**: NPP anomalies in the permanently stratified oceans (grey symbols, left axis) are highly correlated (r^2=0.77) with the MEI of climate variability (red symbols, right axis). **b**: Changes in ocean stratification (red symbols, right axis) link climate variability to ocean biology and are well correlated (r^2=0.73) with NPP anomalies (grey symbols, left axis) in ocean regions with annual average surface temperatures over 15°C. Stratification strength was assessed as the density differences between the surface and a depth of 200m. Note that the MEI and stratification axes (right) increase from top to bottom. (Figure from Behrenfeld et al. 2006).

In the subarctic Northeast Pacific, sea-surface temperatures show a warming trend and salinities a decreasing trend, over the last half-century (Fig. 22) and the stratification of the upper ocean has increased in the subarctic Pacific during recent decades (Freeland et al. 1997: Freeland 2006). Waters off British Columbia were warmer in 2004 and 2005 than the previous 50 years (Whitney 2006a). These changes resulted in decreases in the density of a thin surface layer; increased stability and stratification; declines in the depth of winter mixed-layer depths; and decreased entrainment of nutrients in the euphotic zone. Reduced availability of nitrogen and iron has resulted in limited primary productivity that affects all levels of the food chain (Behrenfeld et al. 2006).

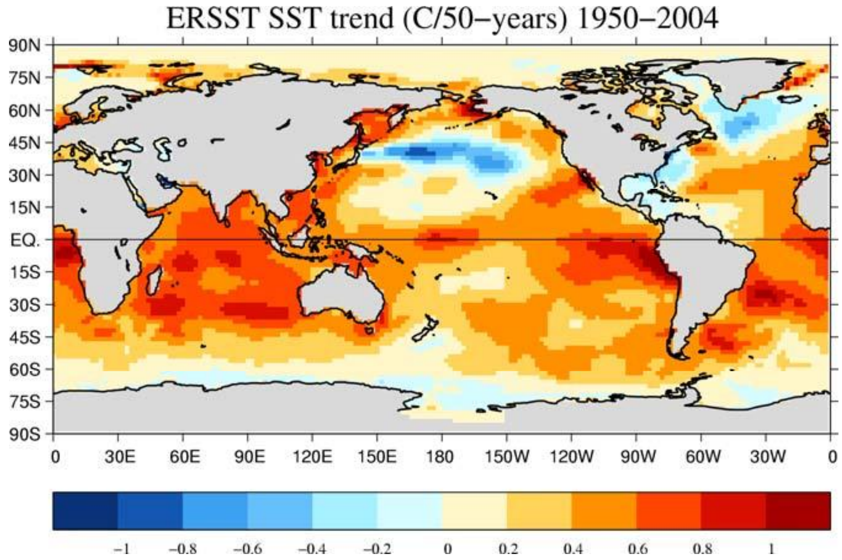

Figure 22: Observed global SST trend from 1950-2004 from NOAA's Extended Reconstructed SST data. Figure produced by Todd Mitchell, University of Washington Joint Institute for the Study of the Atmosphere and Oceans (http://jisao.washington.edu).

This trend of increased stratification also was the situation in the southern regions of the California Current where the abundance of zooplankton deceased by 80% between 1951 and 1993. During this period surface temperatures increased, and increased stratification resulted in less effective injection of nutrients from upwelling (Roemmich and McGowan 1995). However, zooplankton biomass recovered during the four-year cool phase of the PDO (1999-2002) and are at the long-term mean level (see Peterson et al. 2006).

Increased stratification with lower nutrient availability may also have repercussions on the community composition of phytoplankton. Generally warmer nutrient-poor water favors small phytoplankters such as dinoflagellates, whereas cool, nutrient-rich water favors large diatoms which are the basis for a shorter food web for copepods, large herbivores, and salmonids.

Wind-driven Upwelling

Wind-driven upwelling and mixing of nutrient-rich water are major processes that fuel the ecosystem in the California Current and in the Gulf of Alaska. In the California Current, northerly winds during the spring and summer pump cold, nutrient rich waters into the euphotic zone where primary production occurs (Barth et al. 2007). In the Gulf of Alaska, strong cyclonic (counter-clockwise) surface wind stress and tidal mixing pumps nutrients into the euphotic zone. These processes may change with global warming, affecting both ocean productivity and growth and survival of salmonids. Off the Pacific Northwest, both the intensity and timing of upwelling in the spring have been related to salmon survival. Upwelling during April and May of the smolt migration year was correlated with the survival of Oregon Production Index Hatchery (OPIH) coho salmon (Nickelson 1986; Logerwell et al. 2003), and upwelling during April, September and October was related to the return of Snake River Spring Chinook salmon (Scheuerell and Williams 2005).

Bakun (1990) hypothesized that increased greenhouse gas warming will lead to increased contrasts in land-sea temperatures and intensified coastal upwelling in the California Current. This theory has been supported by observations by Mendelssohn and Schwing (2002) and others. Snyder et al. (2003) used a regional climate model to show that wind-driven upwelling in the California Current will intensify, with perhaps increased productivity, but with changes in the upwelling season. Diffenbaugh et al. (2004) predicted feedbacks with warming leading to sparser coastal vegetation, increased land temperatures and land-sea gradients of temperature, and thus more intense upwelling in the northern California Current but a later spring transition. A rapid 20th century increase in coastal upwelling off Northwest Africa was also attributed to land-sea gradients of temperature, which may continue as global warming increases (McGregor et al. 2007).

In the northern California Current, the onset of the spring transition and coastal upwelling in 2005 was about five weeks later than average and effective upwelling of cold water did not occur until about seven weeks after this (Pierce et al. 2006; Kosro et al. 2006). Until late July 2005 surface waters were strongly stratified and anomalously warm, nutrient depleted, and incapable of supporting normal spring-summer primary production.

Delayed onset of upwelling in the spring may reduce the effectiveness of enrichment of the euphotic waters by upwelling (Pennington and Chavez 2000). A late initiation of upwelling, as has occurred during 2005 and 2006, has the potential to miss the peak in ocean-entry timing of spring Chinook, coho, and steelhead from the Columbia River. Delayed upwelling may not be as important for ocean-type Chinook since they enter the ocean over an extended period later in the year and migrate closer to shore than stream-type Chinook or coho salmon. Both the intensity of coastal upwelling and the date of spring transition are correlated with the survival of OPI coho salmon. Hence, changes in either the intensity or the timing of coastal upwelling may significantly impact the ability of the coastal ocean ecosystem to support high growth and survival of salmon exiting their natal streams and rivers, and these changes will likely have different impacts on different stocks and different life history types.

Both upwelling and intrusion of subarctic waters affect the oxygen content in Pacific Northwest waters. During the past several decades declining oxygen levels have been reported in the subarctic Pacific (Emerson et al. 2004; Whitney 2006b), resulting in shoaling of the hypoxic layer from about 400m in the 1950s to about 250m in 2005. This low oxygen water may contribute to the hypoxic conditions that have occurred off the Oregon and Washington coasts during the summer in recent years.

In 2002, anomalously strong southward transports of cold and fresh, low oxygen and nutrient waters from the subarctic Pacific into the coastal zone of Oregon (Freeland et al. 2003) provided conditions favorable for phytoplankton blooms. The phytoplankton production greatly exceeded the capacity of the grazing community to consume the phytoplankton. Much of the excess phytoplankton biomass sank to bottom waters on the shelf and slope, where through bacterial action, it decomposed. This regeneration process reduced oxygen concentrations of the already low concentration waters even further, so much so that in 2002 and 2006, the lack of oxygen caused high mortality of crabs, benthic invertebrates, and benthic fishes. Near-bottom hypoxia has occurred on selected sections of the Oregon coast in all summers since 2002 but was most widespread in 2006, when most regions of the northern Oregon and Washington shelves showed severe hypoxia. However, the biological impacts of these hypoxic conditions are confined to a narrow band along the seafloor of the inner continental shelf during the upwelling season and are not in near-surface waters inhabited by pelagic fishes and salmonids (Grantham et al. 2004). During 2004 and 2005, upwelling was delayed but was intense later in the year. During 2006, the hottest year in U.S. history when July temperatures recorded from terrestrial Oregon stations were four degrees warmer than the 20th century average, upwelling was unusually strong. These limited data suggest, as predicted by Bakun (1990) and Snyder et al. (2003), a possible linkage between global warming, coastal upwelling and, indirectly, the occurrence of hypoxic waters.

Columbia River Salmon

Many other factors that interact with climatic physical forcing, upwelling and stratification influence the ocean survival and migration patterns of salmonids from the Columbia River basin. The effects of climate on productivity, prey resources and predation of salmon will depend on the species, evolutionary significant unit (ESU), distribution and life history. For example, different ESUs of west coast Chinook salmon responded differently to the regime shifts in 1996-97 and 1989-90, with the Snake River spring-summer ESU exhibiting the largest decline (Tolimieri and Levin 2004). Mueter et al. (2002) reported that regional sea-surface temperatures, within several hundred kilometers of a stock's ocean entry point, is a better predictor of survival rates than large-scale climate anomalies such as the PDO, indicating that regional conditions early in ocean life are one of the factors linked to subsequent survival.

Based on projections by the Northwest Power and Conservation Council (2005), natural flows at the Dalles will be higher during the winter and early spring and lower during the summer through early fall. Flows for 2040 are predicted to be lower than historic flows during May and June, the months of peak smolt migration for many stocks of salmonids. Increased temperatures in rearing habitats of salmonids in fresh water, may result in faster growth, and early downstream migrations and ocean entry of smolts (Beckman et al. 1998), if rearing temperatures are not excessive and food is not limited. With earlier peak flows in the Columbia and the projected delay in the onset timing of coastal upwelling (Snyder et al. 2003), the timing of ocean entry of juvenile salmonids may not be optimal. The first few weeks in the ocean are thought to be critical to the survival of salmon off Oregon and Washington (Fisher and Pearcy 1988; Pearcy 1992), so a growing mismatch between smolt migrations and coastal upwelling would likely have significant negative impacts on marine survival rates.

Changing ocean temperatures may alter the behavior, distribution and migrations of salmon, increasing the distance to migrations from their home streams to ocean feeding areas. Pacific salmon are known to have thermal preferences (Manzer et al. 1965) which may change with season. Welch et al. (1998) suggested that warming of the Pacific Ocean associated with a doubling of CO_2 would push the range of sockeye salmon into surface waters of the Bering Sea or farther north. During the 1997 El Niño, Kaeriyama et al. (1998) and Grebmeier et al. (2006) observed that the distribution of several species of salmon were more concentrated in the Bering Sea, leading to intra- and inter-specific competition. However, salmon are not always confined to surface waters. Chinook salmon are known to adjust their vertical distribution in the water column to maintain a range of preferred temperatures (Hinke et al. 2005). Other species make excursions into cool deepwater below the thermocline (Myers et al. 1996), so warm surface waters may not be as limiting as once suspected.

Energetic demands are increased at warmer temperatures, requiring increased consumption of prey to maintain a given growth rate. Growth rates of salmon in the ocean will therefore be affected by sea temperatures and the amount of food available. Hatchery fish may compete with wild fish, decreasing the amount of food available. If salmon migrate farther to the north and/or food is less available, longer times may be required to reach maturity, delaying the usual times of adult migrations into coastal water and rivers. With increased energetic demands, density-dependent competition for food, both interspecific and intraspecific, will likely intensify among maturing salmon on the high seas affecting both growth and survival (Pearcy et al. 1999; Ruggerone et al. 2003; Kaeriyama et al. 2004).

Pelagic Community

Ecosystem production and structure respond to changes in ocean regimes. Between 1998 and 2002, after an intense 1997 El Niño and a prolonged La Niña (summer 1998-2002), species composition of pelagic nekton shifted from a community dominated by southern predatory species (mackerels and hake) to one dominated by northern species (smelts, squid and salmonids (Emmett and Brodeur 2000; Brodeur et al. 2005). Hake, a migratory species from the south is potentially a predator on small juvenile salmonids. They were exceptionally abundant in 1998 during the El Niño, declined during the following cool years (1999-2002) and then increased in 2003 (Fig. 23) During El Niño events and warm PDO cycles, when coastal upwelling is relaxed and the countercurrent is intensified, the latitudinal distribution of pelagic fauna, including predatory fishes, moves north and for some species into the nearshore waters typically occupied by coho and Chinook salmon in the California Current (Pearcy et al. 1985; Lluch-Belda et al. 2005). The spring transition and upwelling were delayed in both 2004 and 2005. This was associated with elevated sea-surface temperatures, stable water column conditions, low productivity and low abundances of forage fishes (Brodeur et al. 2006). In these same years, the voracious Humboldt squid (Dosidicus gigas), a large subtropical species, has been observed far north along the west coast, even into Alaska. This species has the potential to eat large quantities of fish (Ehrhardt 1991; Brodeur et al. 2006; Field et al. Ms).

Fisher and Pearcy (1988) and Pearcy (1992) postulated that predation on juvenile salmonids during early ocean life is a critical factor to their survival. During weak upwelling and warm water conditions, juvenile salmonids, their predators and their prey are concentrated near shore where predation may be intense, especially since warm water predators, such as hake, migrate into northern waters during warm ocean conditions. Presence of alternative prey to juvenile salmonids is thought to be an important buffer to predation. Holtby et al. (1990) reported that predation on juvenile coho salmon was less intense when herring of about the same size were abundant. Emmett et al. (2006) reported the forage fish abundance off the mouth of the Columbia River was low following the 1997/98 ENSO, but increased catches, especially of northern anchovy and whitebait smelt, occurred during cool years with early spring transitions and strong upwelling of 2001 and 2003 (Fig. 23). These trends were correlated with the marine survival of OPI coho salmon. Forage fishes are often about the same size as juvenile salmonids, and are thought to buffer predation on juvenile salmonids in the area. If ocean temperatures increase, cool-water forage species that are alternative prey may decrease, increasing predation on juvenile salmonids.

Seabirds and marine mammals that prey on fishes are also likely be affected by global warming. Caspian terns nesting along the Columbia River may switch to feed more intensely on juvenile salmonids if anchovy and other cool-water forage fishes decline.

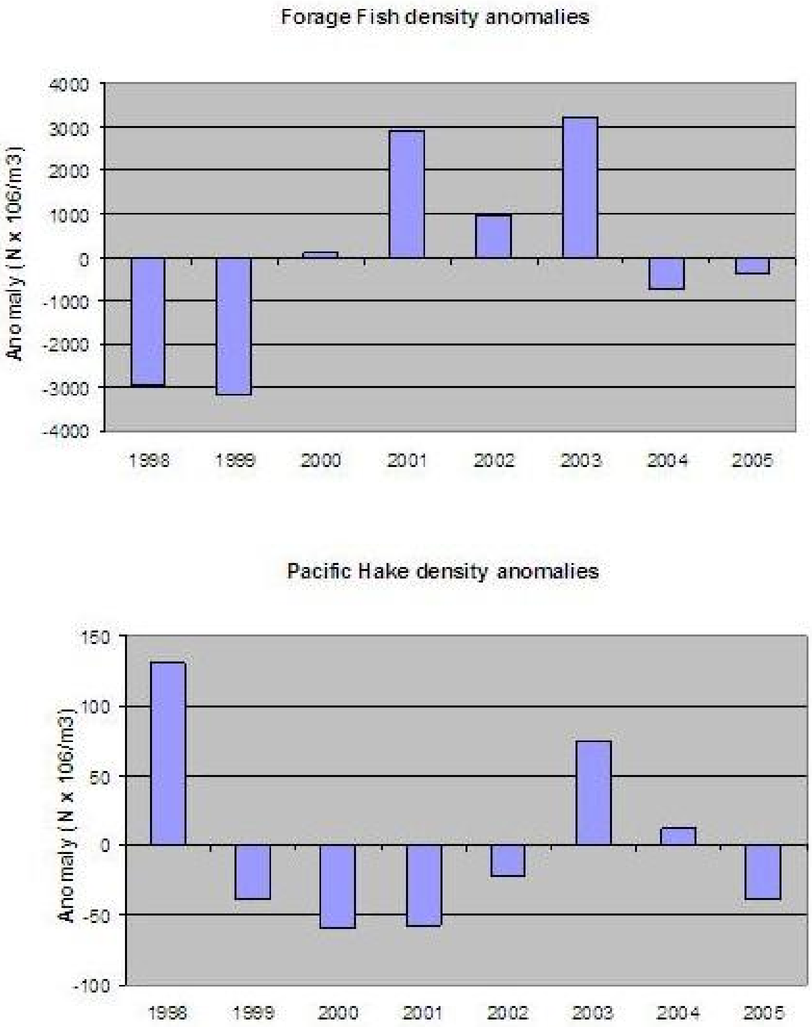

Figure 23. Anomalies in forage–fish and Pacific whiting (hake) abundance, 1996 to 2006. From Emmett et al. (2006).

Ocean Acidification

Evidence is accumulating that carbonate equilibrium of the oceans is changing in response to increasing atmospheric concentrations of CO_2 (Kleypas et al. 2006). Increasing concentrations of CO_2 dissolved in the oceans lowers the pH and decreases the availability of carbonate ions and lowers the saturation state of major shell-forming carbonates in marine animals. This will lead to decreased calcification rates and increased carbonate dissolution, affecting the population dynamics of pelagic communities and abundances and distributions of major calcareous organisms such as coccolithophores, formanifera, and pteropods. Pteropods (pelagic mollusks) that produce

$CaCO_3$ in aragonite form will be more strongly affected than coccolithopores and forminifera which produce the calcite form.

Pteropods are important prey for salmonids in the subarctic Pacific, sometimes comprising up to 40% or more of the diet of some species (Andrievskaya 1958). Pteropods, primarily *Limacina* and *Clio,* are important food for maturing pink, chum, sockeye and coho salmon and steelhead in the northeastern Pacific (LeBrasseur 1966, Allen and Aron 1958). *Limacina* is also prey for juvenile coho salmon in coastal waters off Oregon and Washington (Peterson et al. 1982; Brodeur and Pearcy 1990). The effects of decreased abundance of pteropods on salmonids and pelagic food webs are unknown and would depend on the animals that replaced them in the ecosystem.

Summary of Ocean Impacts

Global climate change in the Pacific Northwest is predicted to result in changes in coastal ecosystems and salmon production that may be similar or potentially even more severe than those experienced during past periods of strong El Niño events and warm phases of the PDO, with warmer upper ocean temperatures, increased stratification and decreased productivity along the coast. However, a lack of certainty in future wind and weather patterns yields large uncertainties for future changes in the characteristics of salmon habitat in the northeast Pacific Ocean. For example, if upwelling winds remain unchanged from those of the past century, coastal upwelling may become less effective at pumping cold, nutrient-rich to the upper ocean because of increased stability in the upper ocean caused by surface warming. Or, as some modeling studies and hypotheses suggest, upwelling winds may become more intense, and perhaps the timing for the upwelling season will change because of timing shifts in upwelling wind patterns. With warmer ocean temperatures we can expect shifts in the size and species composition of zooplankton to smaller lipid-replete zooplankton instead of large, lipid-rich, cool-water species. Because of food chain effects and warm ocean waters, forage fishes will decline and warm-water predators will increase. With less productive coastal waters and modifications in timing of ocean entry, early ocean survival rates for Columbia River salmon will likely decline, and as observed in past periods of poor ocean conditions, declines in adult return rates may be exacerbated by large releases of hatchery fish (Levin et al. 2001).

It is unknown whether the predicted rapid rate of change of new selective forces induced by climate change on salmonids will allow natural selection to produce evolutionary responses that will ameliorate impacts and retain the viability of populations. Such changes have occurred. In less than a century, ocean-type Chinook introduced to New Zealand colonized rivers and evolved significant differences in heritable traits (Quinn et al. 2001; Quinn 2005). The advanced spawning times of hatchery reared salmon is another example of evolutionary change, in this case from artificial selection. In any event, the future will depend on adequate freshwater spawning and rearing habitats, the chain of habitats in the life histories of anadromous salmonids, and maintenance of populations with diverse life histories and phenotypic and genetic variability to provide resilience to future changes.

Integration of Potential Impacts on Salmonids

The impacts of climate change on salmon vary among species and with life history stages but have the potential of impacting virtually every species and life history type of anadromous salmonid in the basin (Tab. 5). Resident cold-water fishes also may be affected (O'Neal 2002). Changes in freshwater ecosystems will impact most dramatically those species that have extended periods of freshwater rearing, but even species with abbreviated freshwater rearing (e.g., chum salmon), may be impacted by higher water temperatures during egg incubation and changes in winter and early spring flows. Impacts of climate change on flow and temperature in the mainstem will impact all species and life history types as will changes in the estuary and the ocean. Climate change has the potential to fundamentally alter the capacity of the Columbia River Basin to produce salmon. It is possible that certain life history types, or even species, may be extirpated from the system if changes are severe enough.

Table 5. Potential impacts of influence of climate warming on salmon life cycle stages. Modified from Healey (2006).

Life Stage	High Temperature Effects
Egg	1) Increased maintenance metabolism will lead to smaller fry. 2) Lower disease resistance may lead to lower survival. 3) Changed thermal regime during incubation may lead to lower survival. 4) Faster embryonic development will lead to earlier hatching. 5) Increased mortality due to more frequent flood flows as snow level rises.
Spring, Summer Rearing	1) Faster yolk utilization may lead to early emergence. 2) Smaller fry are expected to have lower survival rates. 3) Higher maintenance metabolism will lead to greater food demand. 4) Growth rates will be slower if food is limiting or if temperature increases exceed optimal levels or growth could be enhanced food is available and temperatures do not reach stressful levels. 5) Predation risk will increase if temperatures exceed optimal levels.
Overwinter Rearing	1) Smaller size at start of winter is expected to result in lower winter survival. 2) Increased mortality due to more frequent flood flows as snow level rises. 3) Warmer winter would lead to higher metabolic demands, which may also contribute to lower winter survival if food limiting, or higher winter survival if growth and size are enhanced. 4) Warmer winters may increase predator activity/hunger, which can also contribute to lower winter survival.

Smolts	1) Smaller fry entering the winter may lead to smaller potential smolts, which would have a lower survival rate or larger juveniles could have higher survival rates. 2) Smaller fry at end of first summer may cause delay of smolting by one year 3) Faster growth and warmer temperatures could lead to earlier smolting, which may affect marine survival, either positively or negatively.
Estuary and Coastal	1) Changes in smolt timing into the estuary because river flow shifts may lead to a match/mismatch with estuarine/nearshore productivity, which would likely cause altered survival/growth. 2) Increases in predator populations (e.g., hake, mackerel) and prey populations (e.g., changed timing of *Neocalanus dynamics*) may cause increased predation risk/reduced food available, which could contribute to reduced growth and survival during first summer. 3) Higher coastal water temperatures will lead to greater maintenance metabolism, which would cause greater food demand and possibly slower growth/lower survival. 4) Decreases in abundances of cool-water forage fishes could increase predation on juvenile salmonids by fishes, birds, and marine mammals. 5) A warm, stratified ocean with ineffective upwelling could reduced ocean productivity and growth and survival of juvenile salmonids during first summer. 6) Higher coastal water temperatures will lead to greater maintenance metabolism, which would cause greater food demand and possibly slower growth/lower survival.
Open Ocean	1) Warmer North Pacific is expected to reduce thermal habitat for salmon in North Pacific. This may cause changes in ocean salmon distributions, greater density in remaining habitat/greater competition for food, which may contribute to slower growth. 2) A sufficient decline in growth could lead to delayed maturation, increasing marine mortality.
Returning Adults	1) Reduced quality of marine habitats may lead to fewer and smaller adults with lower energy reserves returning to the Columbia. Increased pre-spawning mortality may result. 2) Lower discharge during upstream migration coupled with higher average temperatures could cause greater energy cost during migration, leading to higher pre-spawning mortality. 3) Increased temperatures during migration and spawning may lead to a greater risk of disease outbreak, which would contribute to a greater risk of pre-spawning mortality. 4) Smaller adults will produce fewer, smaller eggs with shorter development times, produce smaller fry, and lead to mis-timed emergence (as detailed in previous life cycle stages above).

In many cases, impacts on the fish at one life history stage due to climate change contribute to increased mortality at later stages (Fig. 24). For example, reduced growth rates due to higher metabolic costs and altered trophic dynamics in freshwater can reduce the growth rate of rearing salmon. The resulting smaller smolts have reduced survival at later life history stages (Koenings et al. 1993). Reduced adult size due to lower food availability and higher metabolic rate in the ocean (Pearcy et al. 1999) may cause an increase in marine mortality and a decrease in body size of returning fish (Cox et al. 1997). Smaller adult fish often suffer increased pre-spawn mortality (Rand et al. 2006) and those that do spawn deposit fewer eggs than would larger fish. Thus, the impacts of climate change can propagate cumulatively through the life of the fish and ultimately impact the productivity of future generations.

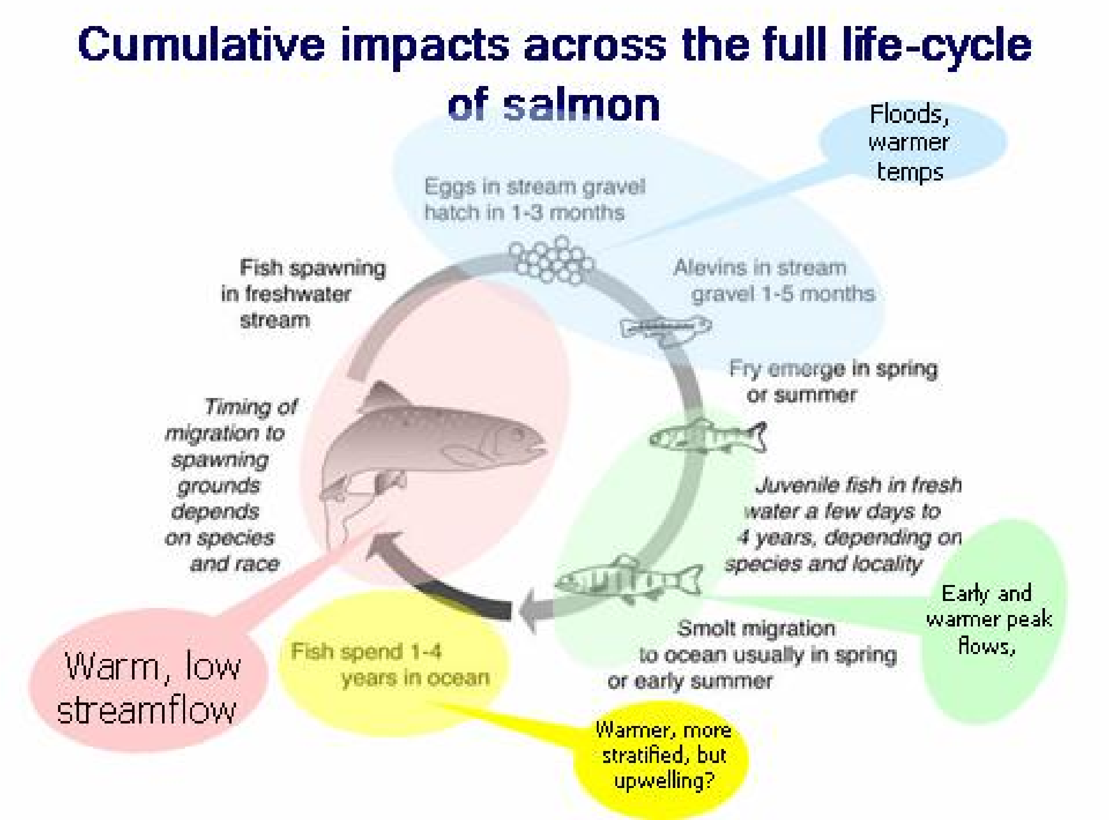

Figure 24. Illustration of the points in the salmon life history where climate change may have an effect. The effects of climate change on salmon cannot be fully understood if impacts on only one stage of their life history are examined; a full appreciation requires examination of the cumulative impacts of all factors that influence salmon during their life cycle. In addition, climate change effects cannot be assessed in isolation from the impacts of other factors influencing habitat or of harvest and hatchery practices (Figure from Mantua presentation to the ISAB, October 2006).

Incorporating Climate Change into Restoration Planning

The increasing certainty that climate in the Columbia Basin will change over the coming decades suggest that inclusion of climate change in fish and wildlife planning will be critical if these plans are to succeed. Inclusion of climate change in planning has been hampered by several factors. In some cases the information on climate change is very technical, making it difficult for planners to interpret the information in a manner relevant to their planning process. The nature of climate change prediction results also can be problematic. These predictions have generally been reported at very coarse spatial scales making it difficult to apply them at the watershed or subbasin scale (Jones et al. 1998). However, climate-change projections at a scale compatible with subbasin planning are becoming more available, making analysis of this issue in future subbasin plans more tractable.

Climate change will occur concurrently with other impacts on fish and wildlife habitat and populations in the Columbia Basin. The recent declines in some fish and wildlife species, and in plant species that constitute their habitat, have been attributed primarily to habitat fragmentation, overexploitation, and global warming (Parmesan and Yohe 2003; Chapin et al. 2006; Mora et al. 2007). Studies that have examined the simultaneous effects of more than a single stressor (e.g., climate and land use; climate, land use, and human population) generally conclude that the effects of more than a single stressor are not easily predictable but may often be more severe than simple combination of the single-factor outcomes. Recently, Mora et al. (2007) used laboratory microcosms to simulate the simultaneous ecological effects of exploitation (harvest), habitat fragmentation (a common result of population increase and human land use), and climate change and concluded that declines in the sizes of populations could be up to 50 times faster when all three factors were simultaneously present. This result, if typical for other species and natural landscapes, implies higher risk of extinction for listed stocks (or other species) that experience land use and resource use impacts simultaneously with climate change impacts.

The forthcoming ISAB report on human population increase and its potential impact on ecosystems in the Columbia Basin will indicate another stressor of fish and wildlife populations in the Columbia Basin whose impact is increasing through time. In areas where human population will increase over the next several decades, fish and wildlife will have to contend with both effects of a warming climate and more intensive land use. Some of the impacts may be additive or synergistic. For example, hydrological impacts caused by climate warming will be compounded by the flow changes caused by development in urbanizing areas. It will be critical for planners to consider both climate change impacts and changes in land use for fish and wildlife restoration efforts in the Columbia Basin to succeed.

Battin et al.'s (2007) recent study of climate change and Chinook restoration scenarios for the Snohomish River Basin offers a promising model for incorporating climate change into other watershed-scale restoration efforts. They used a series of linked models of climate, land cover, hydrology, and salmon population dynamics to investigate the impacts of climate change on the effectiveness of proposed habitat restoration efforts designed to recover depleted Chinook salmon populations in the Snohomish Basin. This study found large, negative impacts on freshwater salmon productivity due to climate change, primarily due to increases in peak flows during egg incubation, with lesser but additional negative impacts due to reduced late summer and early fall spawning flows and increased summer stream temperatures. The modeling suggested that restoration actions and habitat protection can help to mitigate the negative effects of climate change, but that the habitat deterioration associated with changes in streamflows will make salmon recovery targets in the Snohomish Basin hard to meet. The study was able to identify portions of the Snohomish Basin where climate change effects were likely to be most pronounced, and the suggested strategy for restoration was to focus on those areas where increases in winter streamflow, and the associated impact on incubation survival, would be less severe.

To date, however, future impacts on fish and wildlife habitat in the Columbia Basin have been addressed in relatively few planning efforts. In 2005, the Northwest Power and Conservation Council completed one of the largest locally-led watershed planning efforts in the United States, producing separate plans for 58 tributary watersheds or mainstem segments of the Columbia River[4]. The plans guide the implementation of the Council's Columbia River Basin Fish and Wildlife Program, which directs more than $140 million per year of Bonneville electricity revenues to protect, mitigate, and enhance fish and wildlife affected by hydropower dams. The subbasin plans primarily provide this guidance by identification of priority restoration and protection strategies for habitat and fish and wildlife populations and were not intended to regulate land use.

Development of subbasin plans was guided by a subbasin planning template that described the various elements needed to provide contextual information for selection and prioritization of habitat restoration actions. One of these elements was to identify trends in macroclimate and human occupation and use that may affect hydrological or ecological processes in the subbasin over the long term (50 years into the future and beyond). Thus, climate change, or macroclimate trend, was explicitly identified as a component of the planning process. The ISAB and Independent Scientific Review Panel (ISRP) reviewed these plans (ISRP&ISAB 2004-13[5]). One consideration of the reviews was whether potential impacts from climate change or human population growth were considered. Generally, most plans simply recognized that climate change is possible and that human populations are likely to increase. For over 65% of the subbasin plans, the ISAB/ISRP considered the coverage of these issues to be insufficient and considered this deficiency to be a major omission for a forward-looking planning initiative.

Instead of forward-looking, the ISAB/ISRP found that most of the subbasin plans largely documented the history of land conversion, resource consumption, demand for water, and changes in fish and wildlife resources. The focus of the plans was to address the

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[4] See the Council's Web site for a complete description of the subbasin planning process, ISAB and ISRP review, and the adopted plans: www.nwcouncil.org/fw/subbasinplanning/Default.htm.

[5] ISRP and ISAB 2004-13. Scientific Review of Subbasin Plans for the Columbia River Basin Fish and Wildlife Program: www.nwcouncil.org/library/isrp/isrpisab2004-13.htm.

problems caused by human activities over the past 50-100 years but very few attempted to assess what future impact changes in climate or human population might have on subbasin resources and what effect these changes might have on the efficacy of proposed restoration measures. The ISAB/ISRP noted that this approach was like driving down the road looking in the rearview mirror while accelerating. The ISAB/ISRP emphasized that evaluating alternate scenarios for the future is the essence of planning and is crucial to defining realistic restoration opportunities for the future.

In addition, a survey of the plans was conducted for this ISAB climate change review. This survey confirmed that the majority of plans acknowledged the general risk posed by global climate change but did not directly factor it into planning; about one quarter of the plans did not address climate change at all. The survey revealed various levels of integration of climate change into the plans. Some included general discussions that climate change was a global threat that could derail habitat restoration actions at the local level. Others, notably those from Oregon, discussed the prediction of climate models that the Pacific Northwest will become warmer and wetter over the next half century, with an increase in winter precipitation and warmer, drier summers, concluding that such changes could lead to enormous, and mostly negative, impacts on the region's water resources, ecosystems, and plant and animal species' distributions (see Oregon Technical Outreach and Assistance Team (TOAST) 2004). Many of these plans also discussed the confounding effects of localized climate trends and ocean cycles. The Okanogan and Flathead subbasin plans noted contemporary evidence of climate change at the local level, such as changes in lake ecology and receding glaciers. The Deschutes Plan noted that much of the biological diversity within species is expressed at the margins of the habitats for each species and so recommended the importance of maintaining marginal habitats to maintain this diversity. The plan's rationale was that "individuals able to persist in these habitats provide a source of strength for the species should these marginal habitats become more widespread with climate change or normal variation."

Unfortunately, the plans that included a more quantitative discussion of climate change dealt with this issue only in the assessment portion of the plan and the findings were not incorporated into project planning. An exception to this general pattern was the Fifteenmile Subbasin Plan, which recommended consideration of construction of off-channel reservoirs to mitigate for loss of water storage in snowpack. By mentioning this proposal here, the ISAB does not mean to endorse this strategy. Clearly many potential negative impacts on fish and wildlife resources could be associated with reservoir construction. However, this example represented perhaps the only instance in the subbasin planning process where a restoration strategy was proposed specifically to address habitat impacts related to climate change.

The results of the ISAB/ISRP review of the subbasin plans were echoed in a recent assessment of watershed planning in Washington (Whitely Binder 2006). This study found a wide disparity in the extent to which climate change had been considered. This evaluation interviewed 11 of 15 Watershed Planning Leads representing 33 of the 43 Washington Resource Inventory Areas (WRIAs) participating in the Watershed Planning Program and found that climate change was discussed in 15 of the 33 WRIAs covered in the study. Most of these treatments were superficial, including only a sentence or two in the plan to indicate that this phenomenon was occurring. Two of the plans did contain brief technical treatments of climate change impacts for their planning areas.

This report identified factors that can influence the integration of climate change information in watershed planning activities. (Whitely Binder 2006). Six factors were identified:

- Watershed Planning Lead familiarity with climate impacts

Watershed planning groups participating in Washington State's Watershed Planning Program received guidance on the planning process from Department of Ecology Watershed Planning Leads. The familiarity of the Planning Lead (or any other individual serving in an advisory capacity) with climate change impacts can help bring climate impacts into the watershed planning process.

- Interest and knowledge of planning unit members

Planning unit members initiated discussion of climate impacts in 73% of the WRIAs where climate impacts had been discussed, and in these cases there was strong support among a few planning unit members.

- Leadership

Leadership can affect the overall success of watershed partnerships. Leadership may also influence if and how climate change is addressed in the planning effort, although opinions varied on the extent to which strong leadership helped or hindered discussions on climate change.

- Trust among team members:

Trust can plan an important role in determining whether "new" issues like climate change are included in a watershed planning process. Trust creates a process that allows viewpoints to be shared and new information to be sought and developed.

- Willingness to accept new ideas/information

Information that appears to challenge long-term experience, or "genetic knowledge," can create a barrier to including climate change in a watershed planning effort by hindering development of a shared problem among participants.

- Strategic gain

The likelihood that climate change is addressed in planning efforts may increase when climate change impacts are seen as supporting other planning objectives. For example, existing projections for increased drought risk may be used strategically to support proposals for new reservoir construction.

This study also provided some suggestions for future actions that would encourage inclusion of climate change impacts in future planning (Whitely Binder 2006).

- Commitment to updating plans

Regular updating of plans, as envisioned in the subbasin planning process, provides the opportunity for these plans to evolve thorough time and incorporate new issues, like climate change, as they arise.

- Continuation of the planning team

Continuation of the watershed planning teams increases the probability that the knowledge, experience, and personal relationships (i.e., trust) developed through the planning process are maintained.

- Requirement by funding organization to include climate change in plans

The format and content of the plans was largely dictated by the requirements outlined in the planning documentation from the funding agency. A clear mandate to consider climate change likely would encourage a more thorough evaluation of this issue.

- Dedicated funding for inclusion of climate change in plans

Many of the teams would have required some funding to access the necessary expertise to address the technical aspects of climate change. Lack of dedicated funding to address climate change likely made it difficult for planning teams to include climate change in their planning efforts.

- Availability of hydrologic modeling tools

Hydrologic modeling tools create opportunities for planning units to consider how climate change impacts on snowpack and streamflow may affect various watershed management objectives. Adding a climate change assessment capability to new or existing models could enhance efforts to address climate change in watershed planning provided that the effort was cost effective and not too technically difficult.

- Availability of technical support/information

Planning Leads identified several types of information or other support that could help planning units more effectively integrate climate change into the watershed planning process. These included developing information for different types of audiences; providing more detailed, locally-scaled climate change scenarios; providing technical reports from peer-reviewed journals, research groups, and other

> credible sources; developing case studies showing how climate information can be integrated into a plan; providing technical support to planning units; and, finally, providing information on the impacts of climate change on groundwater supplies.

This evaluation clearly indicated that climate change is not yet an important consideration in natural resource planning in Washington. The likelihood that these plans will meet their objectives may be compromised if climate change is not addressed, especially in cases where the resources of focus are sensitive to its potential effects.

For future natural resource planning efforts, a variety of ways are possible to incorporate climate change considerations. Most of the subbasin plans that addressed climate change did so by inputting predicted changes in flow and water temperature to the EDT model. Although the EDT model is considered a "steady-state" model (Mobrand et al. 1997), this approach does provide one method of generating estimates of possible effects of climate change on salmon populations. In addition, Jones et al. (1998) proposed a method they termed an "integrated impact assessment" that coupled climate change projection results with an assessment of how these changes might impact salmon at each stage of their life history. This seems to be a reasonable approach to assessing impacts of climate change on salmon in the Columbia Basin, and similar approaches could be developed for other fish and wildlife resources in the basin. The accuracy and specificity of these approaches will improve as projections of changes in temperature and hydrologic conditions driven by climate change are generated at spatial scales more relevant to fish and wildlife planning. Additional improvements could be attained by addressing some of the impediments and opportunities identified in Whitely Binder (2006).

Snover et al (2003) describe an online *climate change streamflow scenario tool* (www.cses.washington.edu/cig/fpt/ccstreamflowtool/sft.shtml) that is designed to support simple and inexpensive evaluation of a water resource system's vulnerability to climate change in the Columbia Basin. The streamflow scenarios can be directly incorporated into existing planning methods (such as critical period analysis) in place of the historic streamflow record.

The scenarios are currently available at 16 locations in the Columbia River basin (Fig. 25). For each location, there is a 40 year monthly time-step streamflow scenario for the 2020s and for the 2040s as well as simulated historical streamflow for water years 1950-1989. These flow records represent what historical observed (naturalized) flows would be if the average climate of the Pacific Northwest (PNW) changed as projected by global climate models.

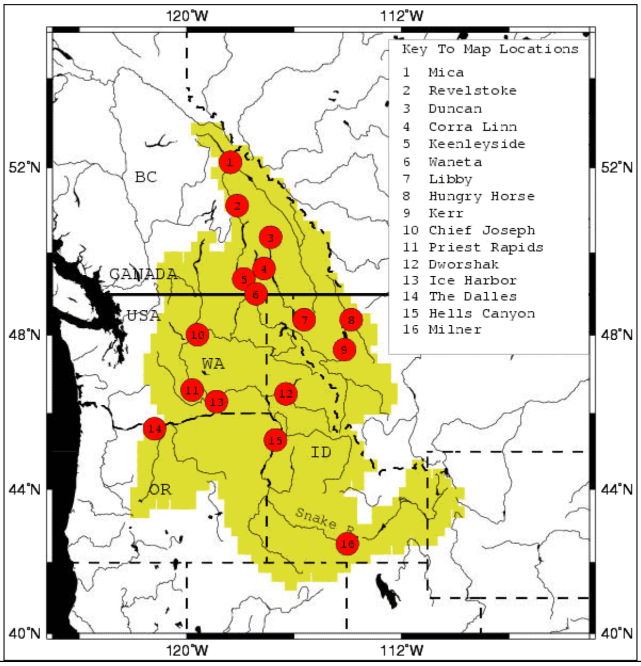

Figure 25: Map of the Columbia Basin indicating locations for which Snover et al. (2003) provide monthly time step climate change impacts on simulated natural streamflow for 1950-89, the decade of the 2020s, and the decade of the 2040s. Figure reproduced from www.cses.washington.edu/cig/fpt/ccstreamflowtool/sftscenarios.shtml.

Mitigating Climate Change Effects

Only global strategies for reducing the emission of greenhouse gases will completely address climate change impacts on all habitats in the Columbia Basin, and even if effective measures were put in place today, changes in the climate would still occur over the next several decades due to previous emissions of greenhouse gases (Tab. 1). Dealing with this issue will require unprecedented cooperation among public and private land stewards and even among nations (Hansen et al. 2001, and many others). As we improve our understanding of climate change (and its interaction with other processes such as population and land use change), uncertainty of future conditions, especially biological conditions, will remain, and policymakers and managers should incorporate the uncertainty in future outcomes into their decision making (Root and Schneider 1993, Hansen et al. 2001, and many others). As we seek solutions to these larger issues, the identification and implementation of actions that may offset some of the negative effects of climate change in the Columbia Basin represent the only near-term, local option for mitigating effects of climate-change.

Below, we provide some general recommendations of the types of actions that might be employed to help address the likely impacts of climate change in the Columbia Basin. However, the specific actions and the locations where they should be deployed must be determined through careful analysis of the regional, or subbasin, sensitivities to climate change. The crucial need to incorporate careful and thorough assessment of climate change in basin planning activities cannot be overstressed.

General Strategies

The scientific foundation of the Fish and Wildlife Program is well-suited to support strategies to mitigate for climate change (NPPC 2000). The role of biodiversity in protecting both contemporary persistence of species and evolutionary potential is recognized in the Fish and Wildlife Program and in many other guidelines for mitigating the damaging effects of climate change. A good example of the value of biodiversity in promoting persistence, evolutionary potential, and various ecosystem functions comes from the literature on Pacific salmon (Hilborn et al. 2003). The sockeye salmon fishery of Bristol Bay is famously productive. Population-scale variability in responses of the salmon to environmental conditions appears to be responsible for maintaining this productivity, as different stocks contribute disproportionately to the spawning complex of fishes in years of different conditions. Ecological theory supports the interpretation that presence of diverse stocks in diverse sites is responsible for the robustness of the Bristol Bay fishery to changing conditions (Chesson and Huntly 1997).

Identification of locations that are likely to be sensitive to climate change and establishment of adequate protective measures, including reserve areas, may be the most effective strategy for maintaining diversity in the face of changing climate in the Columbia Basin (Hansen et al. 2001, Shafer et al. 2001, Halpin 1997). Habitat protection and acquisition efforts are already supported by the FWP, but actions have not yet been targeted to address climate change concerns.

There are several frequently recommended and generally accepted guidelines for selection of reserves or protected areas that are specifically intended to preserve biodiversity in the face of changing climate (summarized in Halpin 1997). These include:

- Select redundant reserves.
- Select reserves that provide habitat diversity (as large as possible, with as much elevational and latitudinal variation as possible, as much topographic heterogeneity as possible, with major vegetation transitions at the cores to avoid movement of a vegetation perimeter outside of the reserve).
- Manage for buffer zone flexibility. Reserves should be surrounded by managed buffer zones that maximize management options under future climate and land-use conditions. Flexible zoning should be established around reserves to allow for land-use modifications and land trades in the future.
- Manage for landscape connectivity. Consider proximity of reserves to other reserves and to unprotected compatible habitat, as well as corridors

to enable movement, recolonization of habitats, and genetic exchange among populations.

- Manage for habitat maintenance, allowing natural disturbances as possible and avoiding as many exogenous stresses (e.g., pollution, non-native species, etc.) as possible.

In addition, a specific guideline for the Columbia River Basin fishes would be:

- Reserves or strongholds for salmonids and cool-water species will be most effective if they include productive populations with diverse life histories and large phenotypic and genetic diversity to provide resilience and evolutionary potential to adapt to climate change.

These recommendations are compatible with the scientific foundation and guidelines of the 2000 FWP, though the current guideline to "Build from strength" requires some modification to take into account the relationships of current and anticipated future strongholds. Halpin (1997) points out an additional concern in applying these guidelines: one must decide whether the goal is to protect the current mix of species over time or provide an arena for protecting changing species diversity.

Additionally, the interplay of human population and land uses with climate change must be considered carefully. The leading cause of habitat loss and species loss or range contraction has been people and their activities (e.g., Laliberte and Rippel 2004, Knick et al. 2003, Dale 1997) and effective planning to mitigate effects of climate change on fish and wildlife must include consideration of and coordination with planning for the population and activities of people.

Community Responses to Changing Environmental Conditions; a Mitigation Caution

Because species differ in their climatic tolerances and optima, as well as in their physiological, behavioral, and evolutionary responses to changing climate, the results of climate change at the community level are difficult to predict. The paleoecological record makes clear that the species assemblages of past climatic conditions have been unique, with combinations of coexisting species, both plant and animal, unlike those observed today. These records suggest that the communities of the future will have different species combinations than now and will be glued together by species interactions that we do not understand and cannot predict with precision. Consequently, strategies to mitigate climate change will not likely be effective if planned at too narrow a scale, whether for single species, single areas, or single habitat types or species assemblages. Managing to accommodate uncertainty requires broader tolerance for error in predicting the expected and so requires broader and more inclusive strategies for protection of species, habitats, and ecosystems.

Possible Actions to Reduce Climate Change Impacts

Mitigation Options for Tributary Habitat

As climate and streams warm, tributary habitats will become increasingly important because they usually provide the cool waters for salmonids and other cool-water species in a watershed. Three actions that could contribute to mitigation of climate change impacts on tributary habitat are provided below; however, to be most effective these actions should be implemented in an integrated manner. A set of considerations relevant to the integration of mitigation actions was provided by Naiman et al. (1993): (1) plan from a broad perspective, rather than from the ecologically incomplete perspective of restoration of isolated components such as fish, vegetation, or restoration of particular stream sections; (2) maintain hydrological connectivity and variability of riparian corridors from the headwaters to the sea; and (3) recognize the environment as a legitimate consumer of water, and strive to achieve a balance between immediate human water needs and long-term environmental and human requirements for water instream and in the riparian corridor.

In general, mitigating for climate-induced changes in hydrology and temperature in tributaries will involve many of the same approaches that have been initiated in the basin to date. Any action that can help minimize increased water temperatures or increase stream flow during summer and autumn would contribute to this end. However, it is unlikely that there are any options to successfully deal with some of the projected changes. For example, there is little that can be done at a local scale that will offset projected changes in snow pack elevation, accumulation, and melt timing.

Temperature increases in some tributaries may be minimized by implementing measures to retain shade along stream channels and augment summer flow. Adequate protection or restoration of riparian buffers along streams is the most effective method of providing summer shade. This action will be most effective in headwater tributaries where shading is crucial for maintaining cool water temperatures. Expanding efforts to protect riparian areas from grazing, logging, development, or other activities that could impact riparian vegetation will help reduce water temperature increases. It will be especially important to ensure that this type of protection is afforded to potential thermal refugia. Removing barriers to fish passage into thermal refugia also should be a high priority. The possible effect of increased fire and insect damage on riparian vegetation due to warming climate was discussed earlier in this report and could reduce the effectiveness of this strategy. Nonetheless, implementing measures to ensure adequate levels of shade will be one of the most effective approaches to limiting temperature increases.

Managing water withdrawals to maintain as high a summer flow as possible could help alleviate both elevated temperatures and low stream flows during summer and autumn. This is very important in areas where decreased snowpack will result in lower and warmer stream flows in the summer. There are a variety of strategies being employed in the Columbia Basin to address stream flow issues. Buying or leasing of water rights and dedicating this flow to the stream has used more frequently in the basin over the last decade. Increased efficiency of diversions and irrigation systems complement this approach. However, this approach typically does not permanently increase water flow, and actions implemented now may not persist long enough to mitigate for climate warming. In addition, water enhancement efforts tend to be implemented at locations where there are willing water rights holders, and these locations may not be the most critical for the fish or wildlife species of interest. Effectively using this strategy to offset impacts from climate change may require targeting the implementation of flow enhancement at sites that will provide the greatest benefit.

Protecting and restoring wetlands, floodplains, or other landscape features that store water also will provide some mitigation for declining summer flow as the climate warms. Watersheds with extensive groundwater reservoirs will be among the most resistant to the impacts of climate change, due to the relatively constant release of cool water from the aquifers that feed the channel networks (Jefferson et al. 2006). Protecting these groundwater systems, and restoring them where possible, may provide refugia for cool-water species, like salmon, during periods of warm temperatures and low flows. Identification and protection of such thermal refugia may be one of the most effective strategies available to mitigate for climate change impacts on salmon and trout. Such locations are utilized by large numbers of fish or by stocks, some that are critically imperiled. These cool-water refugia include many tributaries along the mainstem Columbia where migrating adult salmon and steelhead fish congregate, especially during warm years. These areas need protection as sanctuaries for migrating salmonids, and they might be considered for purchase or conservation easements to ensure that they are buffered from human impacts.

These techniques will be most effective if they are focused on locations where they will be of greatest benefit to the fish and wildlife species of most concern. If the predicted changes occur, the distribution of fish and wildlife populations in the basin will change and many currently suitable habitats will not be so in the future, regardless of actions taken at the local level. Therefore, subbasin plans should consider the potential influence of future climate change when identifying and prioritizing restoration projects.

Mitigation Options for the Mainstem, Estuary, and Plume

Impacts of global warming in the mainstem, estuary and plume must be considered in the context of hydrosystem management. Because the hydrology and salmon habitat of the mainstem and estuary have been extensively transformed, managed and manipulated for decades, there is a range of alternatives for mitigating climate change impacts on Columbia Basin salmon in these habitats. Past changes in hydrosystem infrastructure and operations have already caused enormous changes in the timing, magnitude, and variability in mainstem and lower Columbia River hydrology at seasonal to hourly time scales. To the extent that hydrosystem operations are flexible, there are opportunities to mitigate for some climate change impacts in the estuary and plume because projected changes in natural runoff, even under the most extreme warming scenarios for the late

21st century, are substantially smaller than the changes caused by the development and operation of the hydrosystem in the late 20th century.

Miles et al. (2000) and Payne et al. (2004) have examined climate change impacts on multiple water resource objectives in the Columbia Basin, and both studies identified an unequal distribution of climate change impacts on hydropower generation, recreation, irrigation, instream flow targets, and flood control (Fig. 26; from Miles et al. 2000). Payne et al. (2004) evaluated the potential effects of climate change on the hydrology and water resources of the Columbia River Basin by driving hydrologic and water resources models with changing temperature and precipitation scenarios produced in a global climate model under a "business as usual" greenhouse gas emissions scenario. They note that some of the projected climate change impacts can be mitigated by alternative mainstem hydrosystem operations, there are trade-off between firm hydropower production and instream flow targets for salmon, and there were some impacts that would not be mitigated by the altered operations they evaluated:

> "From the perspective of water resource operations, the projected hydrologic changes would have the greatest effect from spring to autumn, when the reservoir system refills and is intended to maintain storage until the winter reservoir drawdown for flood control and hydropower production. Increasing winter inflows associated with seasonality shifts would necessitate the continuation of present flood control policies despite the decreased ability of the system to replenish current evacuations in the spring. Lower summer streamflows would exacerbate the reduced reservoir refill by increasing drafts for instream flow targets. The lower resulting storage at the end of summer would reduce the ability of the system to meet present firm power production (hydropower 'safe yield') targets during the winter, before reservoir storage begins to be restored by winter precipitation. Hydropower revenues were predicted to be relatively unaffected, however, because annual streamflow volume changes were generally small, and fall and early winter generation reductions would be compensated by increases in late winter and spring.
>
> The starkest result of this study is an evolving tradeoff between reservoir releases to maintain instream flows for fish and hydropower production. In order to maintain performance of the reservoir system with respect to instream flow targets developed under the NMFS Biological Opinion associated with ESA listing of Columbia River salmonids, substantial (10–20%, depending on the future time period) reductions in firm hydropower would be required. Even with these reductions in firm power, late summer minimum flows would still be lower than at present." (Payne et al. 2004).

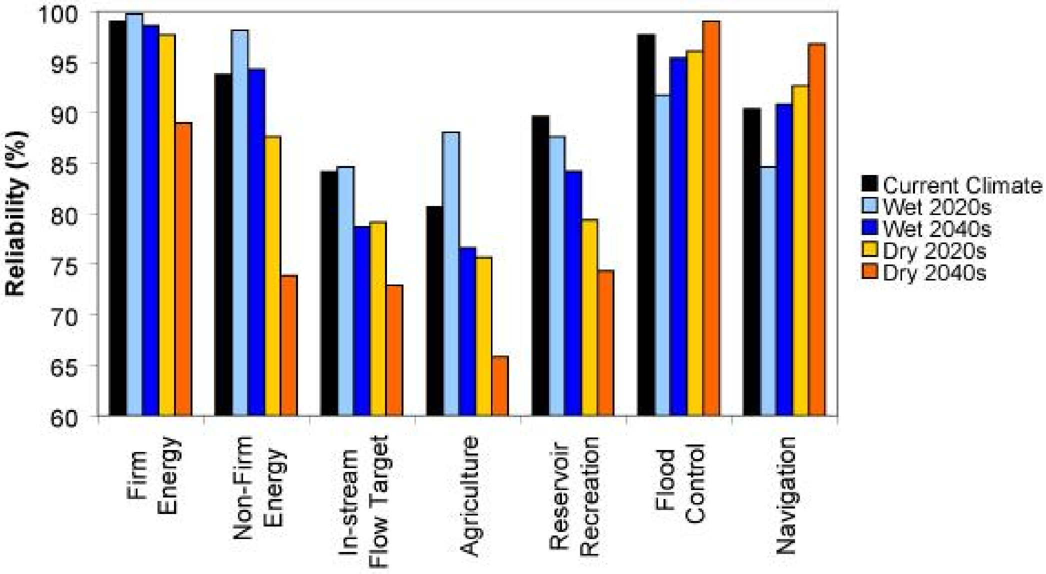

Figure based on data from Miles et al. (2000)
Figure source: Climate Impacts Group, University of Washington

Figure 26. Columbia River Basin reliability by sector for current and future climate under a fixed management policy regime that optimizes flood control and firm hydropower production. The chart shows the simulated reliability of meeting reservoir operation targets estimated using two different climate models (one with a wetter future, the other a dryer future) for the current climate, the 2020s, and the 2040s. Reliability is calculated as the percentage of years that a system target is met. The dark bars represent the control model run, or current climate. It is clear that targets for simulated instream flow, agriculture, and recreation are met less than 100% of the time given the current climate conditions. With the exception of the 2020 projections from the wet models, the projections show losses of reliability in the future for most of the system targets. Figure based on data from Miles et al. (2000). Reproduced from Casola et al. 2005.

Some actions may be possible at mainstem hydroelectric dams in the Columbia and Snake Rivers to help offset projected climate change effects in the mainstem reservoirs and the estuary (i.e., increased water temperatures and reduced river flows during summer and fall). A number of measures are currently used to mitigate for hydroelectric development in the Columbia River Basin and improve juvenile and adult salmonid passage and survival. Below are described several mitigation options that may be considered in the future to help address changes associated with climate change.

Flow augmentation - Flow augmentation from cool/cold water storage reservoirs to reduce water temperatures or create cool water refugia in mainstem reservoirs and the estuary may be an effective strategy to reduce impacts from elevated water temperatures. As reducing water temperature is the goal of this strategy, simply increasing flow may not achieve the desired effect. Water sufficiently cool to impact downstream thermal conditions must be released. Effective implementation of this strategy may require increasing the number of storage reservoirs for additional cool/cold water flow. Careful consideration of the benefits and negative impacts of increasing the number of storage facilities in the basin will be required. Such consideration should occur in the near future if storage capacity is to be increased in time to address impacts of climate change.

<u>Juvenile fish passage</u>- The use of removable surface weirs (RSWs) has proven to be an efficient spillway passage device passing a large number of fish in a relatively small volume of water. Another benefit of RSWs is reducing the time juvenile salmonids spend in the forebay, which will reduce exposure to the warmer surface water temperatures and predators that concentrate there. Juvenile fall Chinook, which move past the dams during summer and fall when water temperatures are high and flows low will especially benefit from the RSWs.

<u>Adult fish passage</u> –There have been recent observations in the summer of adult salmonids delaying dam passage at very high water temperatures. Increasing water temperatures due to climate change may exacerbate this problem. One mitigation option is to reduce water temperatures in the ladders with water drawn from lower cooler strata in the water column of the forebay using large current mixers or exit outflows designed to extract cooler water from lower strata. Covering the ladders to provide shade may also have some effect on water temperature. Cooling water temperatures at ladder exit locations may help encourage fish to enter the ladders.

<u>Transportation</u> – The juvenile fish transportation program run by the U.S. Army Corps of Engineers could develop strategies more focused on temperature criteria for initiating full transport of juvenile fall Chinook. The possibility of transporting immigrating adults through the lower Snake River when water temperatures reach near-lethal limits in the late summer should also be explored.

<u>Reservoir and estuary predation</u> – As indicated above, increases in water temperatures will likely increase predation on juvenile salmonids in mainstem reservoirs and the estuary. One mitigation measure would be an addition of programs by the states to liberalize harvest of introduced piscivorous species such as smallmouth bass, walleye, and channel catfish.

<u>Habitat restoration</u> –Removal of dikes to open backwater, slough and other off-channel habitats along mainstem reservoirs and the estuary can increase flow through these areas and may encourage increased hyporheic flow. Increasing the proportion of flow that is transported below the surface of the river bed or riparian area can substantially cool the water and has been shown to be an important mechanism for the formation of cool water refugia.

Mitigating Effects of Climate Change in the Ocean

If the ocean environment becomes less productive, density dependence will be intensified, resulting in increased competition among species and stocks in the ocean. This may result in lower growth and survival rates for wild salmon in the ocean. Reduction in the hatchery releases during poor ocean conditions may enhance survival of wild stocks, but more research on this topic is needed.

If climate change causes changes in the timing of the spring transition and initiation of coastal upwelling is delayed, as some predict, transportation or inriver passage of juveniles could be controlled so that ocean entry coincides with favorable ocean conditions.

As recommended in the recent ISAB "Report on Harvest Management of Columbia Basin Salmon and Steelhead" (ISAB 2005), harvest management needs a new strategy to adapt to climate changes -- to anticipate and incorporate changes such as PDO and ENSO cycles and global warming in pre-season abundance forecasts and in-season estimates of returning run sizes. Climate change affects identification of the critical needs for (1) maximizing survival of ESA-listed populations, (2) protecting and enhancing important habitats, and (3) managing other factors in the salmon life cycles. During favorable climatic phases "stocks that are below sustainable levels in the poor phase should be allowed to recover their numbers and recolonize or expand areas of freshwater production." Harvest managers need to adopt near- and long-term assessments that consider changing climate in setting annual quotas and harvest levels for fish from the Columbia Basin.

Harvest of salmon in the ocean differentially affects wild and hatchery stocks. Stock identification at sea is already used and could provide a mechanism to determine if stocks are segregated in time or space so that fisheries could target only hatchery stocks or robust wild stocks. Harvest also could be further modified to favor wild populations or ESA-listed ESUs, especially when ocean conditions are not favorable. Harvest management strategies that would achieve this goal include 1) reducing overall harvest levels to help improve survival of wild adults and 2) reducing the allowable levels of take on wild fish in mixed hatchery-wild fisheries.

The Role of the NPCC in Addressing Climate Change in the Columbia Basin

The roles played by the Northwest Power and Conservation Council enable this organization to be an influential force in forging the strategy by which climate change impacts will be addressed in both the Columbia Basin and the Pacific Northwest in general. The Council's responsibilities for regional power planning and implementing a fish and wildlife program place the Council in a position to influence both the human factors that are driving climate change and the management of the natural resources that will be impacted by these changes. The three primary tasks of the Council are:

1. Develop a 20-year electric power plan that will guarantee adequate and reliable energy at the lowest economic and environmental cost to the Northwest
2. Develop a program to protect and rebuild fish and wildlife populations affected by hydropower development in the Columbia River Basin
3. Educate and involve the public in the Council's decision-making processes.

All of these tasks relate to how the region will deal with climate change. The efficient production, distribution, and consumption of power, especially power generated without the release of greenhouse gases, can contribute to global efforts to reduce human impacts on the greenhouse effect and thus reduce human-caused global change over the long term. Incorporating climate change into future fish and wildlife recovery plans can help to ensure that all reasonable measures are taken to buffer the natural ecosystems of the Columbia Basin from the changes in temperature and hydrology expected over the coming decades. The educational mandate of the Council provides a mechanism for encouraging the residents of the basin to become engaged in the coordinated effort that will be required to ensure that the progress that has been made in restoring fish and wildlife populations continues into the future, despite a changing climate.

Key Findings

- Climate records show that the Northwest has warmed about 1.0 ºC since 1900, or about 50% more than the global average warming over the same period (Mote 2003a). The warming rate for the Pacific Northwest over the next century is projected to be in the range of 0.1-0.6˚ C/decade. Projected precipitation changes for the region are relatively modest. Most models project long-term increases in winter precipitation and decreases in summer precipitation. The changes in temperature and precipitation will have impacts on the snow pack, stream flow, and water quality in the Columbia Basin.
- Virtually all future climate scenarios predict increases in wildfire in western North America. Fire frequency and intensity have already increased, with more frequent, larger, and more intense fires in the past 50, and especially the past 15, years in the shrub steppe and forested regions of the West, including the Columbia Basin.
- It is expected that global warming will cause insect outbreaks to become more common and widespread. Drought and hot, dry weather have already led to an increase in insect outbreaks in the Columbia Basin, especially outbreaks of mountain pine beetle.

- Several community types in the Columbia River Basin are likely to decrease greatly in area or disappear regionally, including alpine habitats, subalpine spruce-fir forests, aspen, and sagebrush. Shifts in the distributions of forest tree species will be complex, depending on altered temperature and water availability, summer maximum and winter minimum temperatures, and changing frequencies of fire and insect outbreaks.

- Predicting the effects of global warming on wildlife is complicated because wildlife will be impacted by changing conditions of temperature and moisture and also by the resulting shifts in vegetation, which they depend on for habitat and food. However, populations relying on habitat types that are likely to decrease will decline. For example, the bird species of shrubland and grassland are declining more rapidly than any other avian species group in North America. This habitat type is expected to become increasingly rare as the climate changes over the next century.

- An analysis of the effects of temperature increases associated with climate change suggests that 2% to 7% of current trout habitat in the Pacific Northwest will be unsuitable for these fishes by 2030, 5%-20% by 2060 and 8% to 33% by 2090. Salmon habitat may be more severely affected, in part because these fishes can only occupy areas below barriers and are thus restricted to lower elevations within the region. Predicted loss of salmon habitat would be most severe in Oregon and Idaho with potential losses exceeding 40% by 2090. Loss of salmon habitat in Washington would be less severe, about 22% loss by 2090.

- Lower-elevation tributaries, streams east of the Cascade Mountain crest and in the southern portions of the Columbia Basin would be expected to be most affected by temperature changes due to climate change.

- Watersheds that are just above the current snow line will experience a change from a snow-melt dominated hydrologic regime to one that is driven primarily by winter rainfall or rain on transient snow pack. Even those watersheds which remain above the snow line will experience earlier snow-melt runoff.

- Increased frequency and severity of flood flows during winter can affect over-wintering juvenile fish and incubating eggs in the streambed. Eggs of fall- and winter-spawning fish, including Chinook, coho, chum, and sockeye salmon and bull trout, may suffer higher levels of mortality when exposed to increased flood flows. Higher winter water temperatures also could accelerate embryo development and cause premature emergence of fry.

- Bull trout require cold, headwater streams for spawning. Therefore, a warming climate may disproportionately impact this species. Recent projections predict 22% to 92%.loss of habitat suitable for bull trout in the Columbia Basin as a result of climate warming.

- Warmer water temperatures may exclude salmonids from reaches with temperatures that are already close to their upper thermal limit. Even where water temperatures do not exclude use by salmonids, metabolic rates will increase, leading to reduced growth rates where food is limited and smaller size at the end of the summer. Smaller fish typically suffer higher mortality rates during winter than do larger fish.

- Higher winter temperatures may enable fish to feed more actively, increasing growth rates if sufficient food is available. If food is limited, the elevated metabolic demands created by elevated winter temperatures could reduce winter growth rates and contribute to reduced smolt size the following spring. Larger smolts have higher marine survival.
- The changes in mainstem flows due to hydrosystem operations are substantially greater than the natural runoff changes projected to be caused by climate warming in the 21st century. Current predictions suggest climate change will produce higher flows in winter and early spring due to an increase in the proportion of precipitation falling as rain and less snow storage. Late spring to autumn flows could be reduced.
- The increased water temperatures in the mainstem caused by development of the hydropower system will be exacerbated by climate change. Climate modeling of future water temperatures in the Columbia and Snake rivers predicts an increase of 1o C or greater by 2040, adding to the increases caused by the hydrosystem.
- Fall Chinook spawn in the mainstem of the Snake and Columbia rivers. Increases in water temperature will accelerate the rate of egg development and lead to earlier emergence, most likely at a smaller average size than historically. Smaller-sized fry are likely to have lower survival due to increased vulnerability to predators.
- Predation on salmonids will likely be increased by elevated water temperatures. Northern pikeminnow generally select smaller fish when feeding on juvenile salmonids. Warmer temperatures may reduce the size of smolts. Elevated water temperatures also will increase consumption rates and growth rates of predators.
- Potential impacts of increased water temperatures on adult salmon include delay in dam passage, failure to enter fish ladders, increased fallback, and loss of energy reserves due to increased metabolic demand. Increases in mortality also may be caused by fish pathogens and parasites as these organisms often do not become injurious until their host is thermally stressed.
- Sea level rise in conjunction with higher winter river flows could cause the degradation of estuary habitats created by sediment deposition owing to increased wave damage during storms.
- Numerous warm-water adapted fish, including several non-indigenous species, normally found in freshwater may expand their populations with the warmer water and seasonal expansion of freshwater habitats. The potential impacts on salmon are not understood.
- Climate change may affect the trophic dynamics of the estuary due to upstream extension of the salt wedge in spring early summer due to reduced river flows. The landward head of the salt wedge is characterized by a turbulent region known as the estuary turbidity maximum, an area with high concentrations of fish-food

organisms such as harpacticoid copepods. Changes in the distribution of the salt wedge will influence the location of this zone, but it is difficult to forecast the effect this change will have on juvenile salmon.

- Earlier snowmelt and earlier, higher spring flows and warmer temperatures may cause spring Chinook and steelhead yearlings to smolt and emigrate to the estuary and ocean earlier in the spring. Earlier emigration coupled with the projected delay in the onset timing of coastal upwelling may cause juveniles to arrive in the estuary and ocean prior to the onset of favorable conditions. The first few weeks in the ocean are thought to be critical to the survival of salmon off Oregon and Washington; thus, a growing mismatch between smolt migrations and coastal upwelling would likely have significant negative impacts on marine survival rates.
- Global climate change in the Pacific Northwest is predicted to result in changes in coastal ecosystems and salmon production that may be similar to those experienced during past periods of strong El Niño events and warm phases of the PDO, with warmer upper ocean temperatures, increased stratification and decreased productivity along the coast. However, a lack of certainty in future wind and weather patterns yields large uncertainties for future changes in the characteristics of salmon habitat in the northeast Pacific Ocean.
- Evidence is accumulating that carbonate equilibrium of the oceans is changing in response to increasing atmospheric concentrations of CO_2. Increasing concentrations of CO_2 dissolved in the oceans lowers the pH and decreases the availability of carbonate ions and lowers the saturation state of major shell-forming carbonates in marine animals. Pteropods are expected to be especially impacted, and they can comprise up to 40% or more of the diet of some salmon species.
- Changing ocean temperatures may alter the behavior, distribution and migrations of salmon, increasing the distance from their home streams to ocean feeding areas. Energetic demands are increased at warmer temperatures, requiring increased consumption of prey to maintain a given growth rate. If salmon migrate farther to the north and/or food is less available, longer times may be required to reach maturity, delaying the usual times of adult migrations into coastal water and rivers.
- In many cases, impacts of climate change on a fish at one life history stage contribute to increased mortality at later stages. The impacts of climate change can propagate cumulatively through the life of the fish.
- Climate change will occur concurrently with other impacts in the Columbia Basin. Studies of the simultaneous effects of more than a single stressor (e.g., climate and land use; climate, land use, and human population growth) generally conclude that the effects of more than a single stressor are not easily predictable, but may often be more severe than a simple combination of the single-factor outcomes.
- Future impacts of climate change on fish and wildlife habitat in the Columbia Basin were poorly addressed in the subbasin planning process. The majority of

plans acknowledged the general risk posed by global climate change but did not directly factor it into planning; about one quarter of the plans did not address climate change at all. Very few subbasin plans attempted to assess what future impact changes in climate might have on subbasin resources and what effect these changes might have on the efficacy of restoration measures.

- Inclusion of climate change in planning has been difficult because the information on climate change is very technical, making it difficult for planners to interpret the information in a manner relevant to planning, and climate projections have generally been reported at very coarse spatial scales, making them difficult to apply at the watershed or subbasin scale. Climate-change projections at a scale compatible with subbasin planning are becoming more available, making analysis of this issue in future subbasin plans more tractable.

Recommendations

- Assessing potential climate change impacts in each subbasin and developing a strategy to address these concerns should be a requirement in subbasin plan updates. Providing technical assistance to planners in addressing climate change may help ensure that this issue is addressed thoroughly and consistently in the subbasin plans.
- Tools and climate change projections that will aid planners in assessing subbasin impacts of climate change are becoming more available. Of particular interest for the Columbia Basin is an online climate change streamflow scenario tool that is designed to evaluate vulnerability to climate change for watersheds in the Columbia Basin (www.cses.washington.edu/cig/fpt/ccstreamflowtool/sft.shtml). Models like this one can be used by planners to identify sensitivities to climate change and develop restoration activities to address these issues.
- Although actions that will reverse the process of global climate change cannot be effectively implemented at the scale of the Columbia Basin (these must be global in scale), there are actions that may be beneficial in mitigating some of the impacts of climate change in the basin.
- Locations that are likely to be sensitive to climate change and have high ecological value would be appropriate places to establish reserves through purchase of land or conservation easements. Landscape-scale considerations will be critical in choice of reserve sites, as habitat fragmentation and changes of habitat will influence the ability of such reserves to support particular biota in the future. These types of efforts are already supported by the Fish and Wildlife Program, but actions have not yet been targeted to address climate change concerns.
- Actions that minimize water temperature increases or augment stream flow during summer and autumn would contribute to the mitigation of some climate-induced changes in hydrology and temperature in tributaries. However, there are no

options for addressing some of the projected changes. For example, there is little that can be done at a local scale that will offset projected changes in snow pack elevation, accumulation and melt timing.

- Possible actions that could be taken on the mainstem to address climate change impacts include:
  - Flow augmentation from cool/cold water storage reservoirs to reduce water temperatures or create cool water refugia in mainstem reservoirs and the estuary. Effective implementation of this strategy may require increasing the number of storage reservoirs. Careful consideration of the benefits and negative impacts of increasing the number of storage facilities in the basin will be required. Such consideration should occur in the near future if storage capacity is to be increased in time to address climate change impacts.
  - Use of removable surface weirs to reduce the time juvenile salmonids spend in the warm water of the forebay.
  - Reduction of water temperatures in the ladders with water drawn from lower, cooler strata in the water column of the forebay.
  - Development of transportation strategies more focused on temperature criteria for initiating full transport of juvenile fall Chinook.
  - Evaluation of the possibility of transporting immigrating adults through the lower Snake River when water temperatures reach near lethal limits in the late summer.
  - Liberalization of harvest of introduced piscivorous species such as smallmouth bass, walleye, and channel catfish.
  - Opening of backwater, slough, and other off-channel habitats along mainstem reservoirs and the estuary to encourage an increase in flow through these areas to help reduce water temperature.
- Flow augmentation from cool/cold water storage reservoirs may be an effective strategy to reduce impacts from elevated water temperatures.
- There are opportunities to mitigate for some climate change impacts in the estuary and plume with changes to hydrosystem operations. Possible actions would include reducing the frequency and magnitude of winter flows, extending the period of spring runoff later in the year and increasing late summer and autumn flows.
- If the ocean environment becomes less productive, density-dependent interactions will be intensified. This may result in lower growth and survival rates for wild salmon in the ocean. If this occurs, reduction in hatchery releases during poor ocean conditions may enhance survival of wild stocks, but more research on this topic is needed.
- If climate change alters the timing of the spring transition and initiation of coastal upwelling is delayed, as some predict, transportation or inriver passage of

juveniles might be controlled so that ocean entry coincides with favorable ocean conditions.

- Harvest management should develop a strategy to adapt to climate changes -- to anticipate and incorporate changes such as PDO and ENSO cycles and global warming in pre-season abundance forecasts and in-season estimates of returning run sizes.

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APPENDIX A. Glossary of Climate Change Terms

This glossary was adapted from California's Climate Change Portal glossary (www.climatechange.ca.gov/glossary/index.html) which combined information from numerous sources:

- (EPA) = United States Environmental Protection Agency http://yosemite.epa.gov/oar/globalwarming.nsf/content/glossary.html - (see also www.globalwarming.org/article.php?uid=123**)**
- (IPCC) =Intergovernmental Panel on Climate Change www.ipcc.ch/pub/syrgloss.pdf (Australia) = Green House Office of the Commonwealth of Australia (Australia)
- (CAN) = - Climate Action Network - www.climatenetwork.org/pages/canglossary.html
- (BBC) = http://news.bbc.co.uk/1/hi/sci/tech/1015162.stm - BBC News / Science & Technology / Climate Change Glossary, 10 November, 2000
- (CalSpace) = http://calspace.ucsd.edu/virtualmuseum/Glossary_Climate/
- (Exploratorium) = www.exploratorium.edu/climate/glossary/

The glossary also includes terms from:

- **(**NOAA Paleo) NOAA's National Climatic Data Center (paleo perspective glossary) www.ncdc.noaa.gov/paleo/abrupt/glossary.html
- (Pew) the Pew Center www.pewclimate.org/global-warming-basics/full_glossary/.
- (Wikipedia): wikipedia.org/wiki/Glossary_of_climate_change
- As well as terms defined by the ISAB.

Many terms pertaining to international and governmental agreements are not included in the ISAB glossary but can be found in California's glossary.

Abrupt climate change. Transition of the climate system into a different state (of temperature, rainfall, and other aspects) on a time scale that is faster than the responsible forcing (mechanistic); change of the climate system that is faster than the adaptation time of social and/or ecosystems (impacts). (NOAA Paleo)

Absorption lines. Any portion of the electromagnetic spectrum (including visible light) that is trapped by free atoms or molecules in the path of the radiation, thus reducing their transmission. In the climate context, this is important for the greenhouse effect since water vapor, carbon dioxide and methane absorb certain wavelengths of infrared radiation. (Calspace)

Absorption of Radiation. The uptake of radiation by a solid body, liquid or gas. The absorbed energy may be transferred or re-emitted. (EPA)

Aerosols. Particles of matter, solid or liquid, larger than a molecule but small enough to remain suspended in the atmosphere. Natural sources include salt particles from sea spray and clay particles as a result of weathering of rocks, both of which are carried upward by the wind.

Aerosols can also originate as a result of human activities and in this case are often considered pollutants. See also Sulfate Aerosols. (EPA)

Afforestation. The Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Inventory Guidelines defines afforestation as the planting of new forests on land which historically been covered by forest. (Australia)

Albedo. The ratio of reflected to incident light; albedo can be expressed as either a percentage or a fraction of 1. Snow covered areas have a high albedo (up to about 0.9 or 90%) due to their white color, while vegetation has a low albedo (generally about 0.1 or 10%) due to the dark color and light absorbed for photosynthesis. Clouds have an intermediate albedo and are the most important contributor to the Earth's albedo. The Earth's aggregate albedo is approximately 0.3. (EPA)

Aleutian Low. The Aleutian Low is a statistical feature of the winter circulation that dominates the winter climate of the North Pacific. Its existence relies on the frequent development of eastward moving winter storms along a more-or-less regular path. While the individual winter cyclones have a typical lifetime of one to a few days, the Aleutian Low pressure cell is prominent from October through March, the months of frequent winter storm development over the North Pacific and Aleutian Islands region. Variations in the location and intensity of the Aleutian Low contribute to large variations in Pacific Northwest climate and ocean conditions in the Northeast Pacific. (ISAB)

Anthropogenic. Derived from human activities. (EPA)

Atmosphere. The mixture of gases surrounding the Earth. The Earth's atmosphere consists of about 79.1% nitrogen (by volume), 20.9% oxygen, 0.036% carbon dioxide and trace amounts of other gases. The atmosphere can be divided into a number of layers according to its mixing or chemical characteristics, generally determined by its thermal properties (temperature). The layer nearest the Earth is the troposphere, which reaches up to an altitude of about 8 km (about 5 miles) in the polar regions and up to 17 km (nearly 11 miles) above the equator. The stratosphere, which reaches to an altitude of about 50km (31 miles) lies atop the troposphere. The mesosphere which extends up to 80-90 km is atop the stratosphere, and finally, the thermosphere, or ionosphere, gradually diminishes and forms a fuzzy border with outer space. There is relatively little mixing of gases between layers. (EPA)

Baseline Emissions. The emissions that would occur without policy intervention (in a business-as-usual scenario). Baseline estimates are needed to determine the effectiveness of emissions reduction programs (often called mitigation strategies). (EPA)

Benthic Foraminifera. Single-celled animals that live near the sediment water interface and have calcium carbonate skeletons. The skeletons of benthic foraminifers are often preserved in ocean sediments, providing a rich fossil record of the environmental conditions of the water. (NOAA Paleo)

Biodiversity. The variety of organisms found within a specified geographic region. (Pew)

Biogeochemical Cycle. The chemical interactions that take place among the atmosphere, biosphere, hydrosphere, and geosphere. (EPA)

Biomass Energy. Energy produced by combusting renewable biomass materials such as wood. The carbon dioxide emitted from burning biomass will not increase total atmospheric carbon dioxide if this consumption is done on a sustainable basis (i.e., if in a given period of time, regrowth of biomass takes up as much carbon dioxide as is released from biomass combustion).

Biomass energy is often suggested as a replacement for fossil fuel combustion which has large greenhouse gas emissions. (EPA)

Biomass. Organic nonfossil material of biological origin. For example, trees and plants are biomass. (EPA)

Biosphere. The region on land, in the oceans, and in the atmosphere inhabited by living organisms. (EPA)

Black Carbon Aerosols. Particles of carbon in the atmosphere produced by inefficient combustion of fossil fuels or biomass. Black carbon aerosols absorb light from the sun, shading and cooling the Earth's surface, but contribute to significant warming of the atmosphere (see "radiative forcing"). (Pew)

Calcium carbonate (CaCO3). A molecule consisting of calcium, carbon and oxygen that is secreted by corals, forming their skeleton; it also secreted by mollusks (clams, oysters, etc.), forming their protective shells. (NOAA Paleo)

Carbon Cycle. The global scale exchange of carbon among its reservoirs, namely the atmosphere, oceans, vegetation, soils, and geologic deposits and minerals. This involves components in food chains, in the atmosphere as carbon dioxide, in the hydrosphere and in the geosphere. (EPA)

Carbon dating. A dating method that uses the disintegration of the 14C atom to determine the age of sample containing carbon. 14C is produced in the atmosphere by cosmic ray bombardment, and has a half-life of 5570 years, making it useful for dating samples in the range of 0-40,000 years. (NOAA Paleo)

Carbon Dioxide (CO2). The greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalents). The major source of CO2 emissions is fossil fuel combustion. CO2 emissions are also a product of forest clearing, biomass burning, and non-energy production processes such as cement production. Atmospheric concentrations of CO2 have been increasing at a rate of about 0.5% per year and are now about 30% above preindustrial levels. (EPA)

Carbon Sequestration. The uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon. Fossil fuels were at one time biomass and continue to store the carbon until burned. (EPA)

Carbon Sinks. Carbon reservoirs and conditions that take in and store more carbon (carbon sequestration) than they release. Carbon sinks can serve to partially offset greenhouse gas emissions. Forests and oceans are common carbon sinks. (EPA)

Carbonaceous Aerosol(s). Aerosol(s) (q.v.) containing carbon. (IPCC)

Columbia Basin Index (CBI). Developed by Petersen and Kitchell (2001), the CBI is an index specific to the Columbia River based on unregulated flows (1938-1999) to describe historical climate changes within the Basin. (ISAB)

Chlorofluorocarbons and Related Compounds. This family of anthropogenic compounds includes chlorofluorcarbons (CFCs), bromofluorcarbons (halons), methyl chloroform, carbon tetrachloride, methyl bromide, and hydrochlorofluorcarbons (HCFCs). These compounds have been shown to deplete stratospheric ozone, and therefore are typically referred to as ozone depleting substances. The most ozone-depleting of these compounds are being phased out under the Montreal Protocol. (EPA)

Chronology. A general term for the age-depth relationship in ice, sediment, or another deposit. Ages are usually measured for discrete samples, and the ages of intermediate samples is interpolated between samples with measured ages. (NOAA Paleo)

Climate Change (also referred to as "global climate change"). The term "climate change" is sometimes used to refer to all forms of climatic inconsistency, but because the Earth's climate is never static, the term is more properly used to imply a significant change from one climatic condition to another. In some cases, climate change' has been used synonymously with the term, "global warming"; scientists however, tend to use the term in the wider sense to also include natural changes in climate. See also Enhanced Greenhouse Effect. (EPA)

Climate Feedback. An atmospheric, oceanic, terrestrial, or other process that is activated by the direct climate change induced by changes in radiative forcing. Climate feedbacks may increase (positive feedback) or diminish (negative feedback) the magnitude of the direct climate change. (EPA)

Climate Lag. The delay that occurs in climate change as a result of some factor that changes only very slowly. For example, the effects of releasing more carbon dioxide into the atmosphere may not be known for some time because a large fraction is dissolved in the ocean and only released to the atmosphere many years later. (EPA)

Climate Model. A quantitative way of representing the interactions of the atmosphere, oceans, land surface, and ice. Models can range from relatively simple to quite comprehensive. Also see General Circulation Model. (EPA)

Climate Modeling. The simulation of the climate using computer-based models. Also see General Circulation Model. (EPA)

Climate Sensitivity. The equilibrium response of the climate to a change in radiative forcing; for example, a doubling of the carbon dioxide concentration. (EPA)

Climate System (or Earth System). The atmosphere, the oceans, the biosphere, the cryosphere, and the geosphere, together make up the climate system. (EPA)

Climate Variability. Refers to changes in patterns, such as precipitation patterns, in the weather and climate. (Pew)

Climate. The average weather (usually taken over a 30-year time period) for a particular region and time period. Climate is not the same as weather, but rather, it is the average pattern of weather for a particular region. Weather describes the short-term state of the atmosphere. Climatic elements include precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost, and hail storms, and other measures of the weather. (EPA)

Climatic feedback mechanisms. A feedback is an enhancement (positive feedback) or a damping (negative feedback) of an initial change, in this case in the climate system. For example, when less energy reaches the earth, temperature decreases and the area covered by snow increases. The albedo of the planet decreases, reflecting more energy towards the atmosphere. Consequently less energy is available at the surface, and temperature further decreases. The whole "cycle" from the initial cooling to the further cooling is a feedback. It is a positive feedback in this example. (NOAA Paleo)

Cloud Condensation Nuclei. Airborne particles that serve as an initial site for the condensation of liquid water and which can lead to the formation of cloud droplets. (IPCC)

CO2 Fertilization. Te enhancement of plant growth as a result of elevated atmospheric CO2 concentrations. (IPCC)

Cryosphere. The part of the Earth's surface that is perennially frozen or below the freezing point. (CA)

Deforestation. Those practices or processes that result in the change of forested lands to non-forest uses. This is often cited as one of the major causes of the enhanced greenhouse effect for two reasons: 1) the burning or decomposition of the wood releases carbon dioxide; and 2) trees that once removed carbon dioxide from the atmosphere in the process of photosynthesis are no longer present and contributing to carbon storage. (EPA)

Dendrochronology. A science based on the exact calendar dating of annual growth rings in wood. (NOAA Paleo)

Dendroclimatology. A subfield of **dendrochronology**, which investigates the climatic effect on tree growth, and uses dated tree rings to reconstruct and study past and present climate. (NOAA Paleo)

Desertification. The progressive destruction or degradation of existing vegetative cover to form desert. This can occur due to overgrazing, deforestation, drought, and the burning of extensive areas. Once formed, deserts can only support a sparse range of vegetation. Climatic effects associated with this phenomenon include increased albedo, reduced atmospheric humidity, and greater atmospheric dust (aerosol) loading. (EPA)

Diatom. Single celled phytoplankton that produce silica skeletons. Diatoms are one of the most abundant, widely distributed primary producers in the ocean. Different species of diatoms living in ocean and lakes have affinities for different environmental conditions such as alkalinity, available nutrients, salinity and acidity. (NOAA Paleo)

Diurnal cycle. Mean solar day occurring as Earth rotates from east to west on its axis. (NOAA Paleo)

Diurnal Temperature Range. The difference between maximum and minimum temperature over a period of 24 hours. (IPCC)

Ecosystem. Relationships between and among living organisms and their non-living environment. (NOAA Paleo)

El Niño. A climatic phenomenon occurring irregularly, but generally every 3 to 5 years. El Niños often first become evident during the Christmas season (El Niño means Christ child) in the surface oceans of the eastern tropical Pacific Ocean. The phenomenon involves seasonal changes in the direction of the tropical winds over the Pacific and abnormally warm surface ocean temperatures. The changes in the tropics are most intense in the Pacific region, these changes can disrupt weather patterns throughout the tropics and can extend to higher latitudes, especially in Central and North America. The relationship between these events and global weather patterns are currently the subject of much research in order to enhance prediction of seasonal to interannual fluctuations in the climate. (EPA)

Emissions. The release of a substance (usually a gas when referring to the subject of climate change) into the atmosphere. (EPA)

Enhanced Greenhouse Effect. The natural greenhouse effect has been enhanced by anthropogenic emissions of greenhouse gases. Increased concentrations of carbon dioxide, methane, and nitrous oxide, CFCs, HFCs, PFCs, SF6, NF3, and other photochemically important gases caused by human activities such as fossil fuel consumption and adding waste to landfills, trap more infra-red radiation, thereby exerting a warming influence on the climate. See Climate Change and Global Warming. (EPA)

ENSO. An acronym for El Niño Southern Oscillation (NOAA Paleo)

Equilibrium Response. The steady state response of the climate system (or a climate model) To an imposed radiative forcing. (IPCC)

Equivalent CO2. The concentration of CO2 that would cause the same amount of radiative forcing as a given mixture of CO2 and other greenhouse gasses. (IPCC)

Euphotic Zone. That portion of the water column receiving sufficient light to support photosynthesis. (ISAB)

Evapotranspiration. The sum of evaporation and plant transpiration. Potential evapotranspiration is the amount of water that could be evaporated or transpired at a given temperature and humidity, if there was plenty of water available. Actual evapotranspiration can not be any greater than precipitation and will usually be less because some water will run off in rivers and flow to the oceans. If potential evapotranspiration is greater than actual precipitation, then soils are extremely dry during at least a major part of the year. (EPA)

Evolutionary change. Either phenotypic or genetic changes that occur in an organism from generation to generation through the exchange of genes. (NOAA Paleo)

Feedback Mechanisms. A mechanism that connects one aspect of a system to another. The connection can be either amplifying (positive feedback) or moderating (negative feedback). See also Climate Feedback. (EPA)

Fluorocarbons. Carbon-fluorine compounds that often contain other elements such as hydrogen, chlorine, or bromine. Common fluorocarbons include chlorofluorocarbons and related compounds (also know as ozone depleting substances), hydrofluorocarbons (HFCs), and perfluorcarbons (PFCs).

Flux. Shifts or flows of carbon over time from one pool to another (e.g. from the atmosphere to the forest). (Australia)

Forcing Mechanism. A process that alters the energy balance of the climate system, i.e. changes the relative balance between incoming solar radiation and outgoing infrared radiation from Earth. Such mechanisms include changes in solar irradiance, volcanic eruptions, and enhancement of the natural greenhouse effect by emission of carbon dioxide. See also Radiative Forcing. (EPA)

Fossil air. A sample of air that preserves the composition of the environment at the time it was deposited. Bubbles found in ice cores are one example of fossil air that records the atmospheric composition of the atmosphere at the time the ice was formed. (NOAA Paleo)

Fossil Fuel Combustion. Burning of coal, oil (including gasoline), or natural gas. This burning, usually to generate energy, releases carbon dioxide, as well as combustion by products that can include unburned hydrocarbons, methane, and carbon monoxide. Carbon monoxide, methane, and many of the unburned hydrocarbons slowly oxidize into carbon dioxide in the atmosphere. Common sources of fossil fuel combustion include cars and electric utilities. (EPA)

Fossil Fuel. A general term for combustible geologic deposits of carbon in reduced (organic) form and of biological origin, including coal, oil, natural gas, oil shales, and tar sands. A major concern is that they emit carbon dioxide into the atmosphere when burnt, thus significantly contributing to the enhanced greenhouse effect. (EPA)

General Circulation Model (GCM). A global, three-dimensional computer model of the climate system which can be used to simulate human-induced climate change. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface. (EPA)

Geologic time scale. Relative time scale based on stratigraphic position and correlation, and many different types of chronologic evidence**.** Geologic time is broken down into eons, eras, periods and epochs. (NOAA Paleo)

Geosphere. The soils, sediments, and rock layers of Earth's crust, both continental and beneath the ocean floors. (EPA)

Global Warming Potential (GWP). The index used to translate the level of emissions of various gases into a common measure in order to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emissions of one kilogram of a greenhouse gas to that from emission of one kilogram of carbon dioxide over a period of time (usually 100 years). Gases involved in complex atmospheric chemical processes have not been assigned GWPs due to complications that arise. Greenhouse gases are expressed in terms of Carbon Dioxide Equivalent. The International Panel on Climate Change (IPCC) has presented these GWPs and regularly updates them in new assessments. (CA)

Global Warming. An increase in the near surface temperature of the Earth. Global warming has occurred in the distant past as the result of natural influences, but the term is most often used to refer to the warming predicted to occur as a result of increased emissions of greenhouse gases. Scientists generally agree that the Earth's surface has warmed by about 1 degree Fahrenheit in the past 140 years. The Intergovernmental Panel on Climate Change (IPCC) recently concluded that increased concentrations of greenhouse gases are causing an increase in the Earth's surface temperature and that increased concentrations of sulfate aerosols have led to relative cooling in some regions, generally over and downwind of heavily industrialized areas. Also see Climate Change and Enhanced Greenhouse Effect. (EPA)

Greenhouse Effect. The effect produced as greenhouse gases allow incoming solar radiation to pass through the Earth's atmosphere, but prevent most of the outgoing infra-red radiation from the surface and lower atmosphere from escaping into outer space. This process occurs naturally and has kept the Earth's temperature about 59 degrees F warmer than it would otherwise be. Current life on Earth could not be sustained without the natural greenhouse effect. (EPA)

Greenhouse Gas (GHG). Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs) , ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). (EPA)

Half-life. The time required for half the nuclei in a sample of a specific isotopic species to undergo radioactive decay. (NOAA Paleo)

Heterotrophic. Capable of deriving energy for life processes only from the decomposition of organic compounds, and incapable of using inorganic compounds as sole sources of energy or for organic synthesis. In the estuary, the term refers to energy provided by bacteria associated with decaying organic material. (ISAB)

HGWP (High Global Warming Potential). Some industrially produced gases such as sulfur hexafluoride (SF6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) have extremely high GWPs. Emissions of these gases have a much greater effect on global warming than an equal emission (by weight) of the naturally occurring gases. Most of these gases have GWPs of 1,300 - 23,900 times that of CO2. These GWPs can be compared to the GWPs of CO2, CH4, and N2O which are presently estimated to be 1, 23 and 296, respectively. (Pew)

Hydrocarbons. Substances containing only hydrogen and carbon. Fossil fuels are made up of hydrocarbons. Some hydrocarbon compounds are major air pollutants. (EPA)

Hydrofluorocarbons (HFCs). These chemicals (along with perfluorocarbons) were introduced as alternatives to ozone depleting substances in serving many industrial, commercial, and personal needs. HFCs are emitted as by-products of industrial processes and are also used in manufacturing. They do not significantly deplete the stratospheric ozone layer, but they are powerful greenhouse gases with global warming potentials ranging from 140 (HFC-152a) to 12,100 (HFC-23). (EPA)

Hydrosphere. The part of the Earth composed of water including clouds, oceans, seas, ice caps, glaciers, lakes, rivers, underground water supplies, and atmospheric water vapor. (EPA)

Ice Age. Period during which polar ice extends to much lower latitudes than normal. (NOAA Paleo)

Infra-red Radiation. The heat energy that is emitted from all solids, liquids, and gases. In the context of the greenhouse issue, the term refers to the heat energy emitted by the Earth's surface and its atmosphere. Greenhouse gases strongly absorb this radiation in the Earth's atmosphere, and reradiate some back towards the surface, creating the greenhouse effect. (EPA)

Insolation. Amount of solar radiation received on a given body or in a given area. (NOAA Paleo)

Instrumental record. data measured using instruments, such as thermometers and rain gauges. (NOAA Paleo)

Integrated Assessment. A method of analysis that combines results and models from the physical, biological, economic and social sciences, and the interactions between these components, in a consistent framework, to project the consequences of climate change and the policy responses to it. (IPCC)

Interglacial. A time interval between glacial periods characterized by lack of glacial ice in mid-latitudes, such as modern Holocene climate. (NOAA Paleo)

Intergovernmental Panel on Climate Change. The IPCC was established jointly by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of climate change. The IPCC draws upon hundreds of the world's expert scientists as authors and thousands as expert reviewers. Leading experts on climate change and environmental, social, and economic sciences from some 60 nations have helped the IPCC to prepare periodic assessments of the scientific underpinnings for understanding global climate change and its consequences. With its capacity for reporting on climate change, its consequences, and the viability of adaptation and mitigation measures, the IPCC is also looked to as the official advisory body to the world's governments on the state of the science of the climate change issue. For example, the IPCC organized the development of internationally accepted methods for conducting national greenhouse gas emission inventories. (IPCC)

Isotope. A form of a specific element that has the same number of protons, but differs in the number of neutrons; forms of the same element that have different mass numbers. (NOAA Paleo)

Lifetime (Atmospheric). The lifetime of a greenhouse gas refers to the approximate amount of time it would take for the anthropogenic increment to an atmospheric pollutant concentration to return to its natural level (assuming emissions cease) as a result of either being converted to another chemical compound or being taken out of the atmosphere via a sink. This time depends on the pollutant's sources and sinks as well as its reactivity. The lifetime of a pollutant is often considered in conjunction with the mixing of pollutants in the atmosphere; a long lifetime will allow the pollutant to mix throughout the atmosphere. Average lifetimes can vary from about a week (sulfate aerosols) to more than a century (CFCs, carbon dioxide). (CA)

Littoral cell. Coasts are divided into natural compartments called littoral cells. Each cell contains a complete cycle of sedimentation including sources, transport paths, and sinks. The presence of sand on any particular beach depends on the transport of sand within the cell. When structures such as training walls at the mouth of the Columbia River interfere with sand transport, beaches will erode. (ISAB)

Littoral zone. Area of shore between mean high water and mean low water. (NOAA Paleo)

Marine Biosphere. A collective term for all living marine organisms. (IPCC)

Mauna Loa Record. The record of measurement of atmospheric CO2 concentrations taken at Mauna Loa Observatory, Mauna Loa, Hawaii, since March 1958. This record shows the continuing increase in average annual atmospheric CO2 concentrations. (Pew)

Meltwater plume. Body of fresh water derived from the melting of glacial ice that floats in large bodies of salt water. (NOAA Paleo)

Methane (CH4). A hydrocarbon that is a greenhouse gas with a global warming potential most recently estimated at 24.5. Methane is produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and oil, coal production , and incomplete fossil fuel combustion. The atmospheric concentration of methane has been shown to be increasing at a rate of about 0.6% per year and the concentration of about 1.7 parts per million by volume (ppmv) is more than twice its preindustrial value. However, the rate of increase of methane in the atmosphere may be stabilizing. (EPA)

Natural climate record. A record of climatic events found by examining the natural environment (tree rings, coral growth bands, layers of ice in glaciers). (NOAA Paleo)

Negative Feedback. A process that results in a reduction in the response of a system to an external influence. For example, increased plant productivity in response to global warming would be a negative feedback on warming, because the additional growth would act as a sink for CO2, reducing the atmospheric CO2 concentration. (Pew)

Nitrogen Oxides (NOx). Gases consisting of one molecule of nitrogen and varying numbers of oxygen molecules. Nitrogen oxides are produced in the emissions of vehicle exhausts and from power stations. In the atmosphere, nitrogen oxides can contribute to formation of photochemical ozone (smog), can impair visibility, and have health consequences; they are thus considered pollutants. (EPA)

Nitrous Oxide (N2O). A powerful greenhouse gas with a global warming potential of 320. Major sources of nitrous oxide include soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning. (EPA)

Ocean Acidification. Increasing concentrations of CO2 dissolved in the oceans lowers the pH and decreases the availability of carbonate ions and lowers the saturation state of major shell-forming carbonates in marine animals. (ISAB)

Osmoregulatory. Refers to the process of osmoregulation, the physiological process which maintains a balance of water and ions (particulary sodium and potassium) in a fishes blood.

Oxygen isotope ratio (d18O). An expression for the ratio of the 18O to 16O atoms in a sample relative to a standard, defined as:D18O= (18O/16Osample. 18O/16Ostandard)/ 18O/16Ostandard (NOAA Paleo)

Oxygen isotopes. Oxygen atoms having the same atomic number (protons) but different mass numbers (and different numbers of neutrons). The two stable isotopes of oxygen are 16O and 18O. (NOAA Paleo)

Ozone (O3). Ozone consists of three atoms of oxygen bonded together in contrast to normal atmospheric oxygen which consists of two atoms of oxygen. Ozone is an important greenhouse gas found in both the stratosphere (about 90% of the total atmospheric loading) and the troposphere (about 10%). Ozone has other effects beyond acting as a greenhouse gas. In the stratosphere, ozone provides a protective layer shielding the Earth from ultraviolet radiation and subsequent harmful health effect on humans and the environment. In the troposphere, oxygen molecules in ozone combine with other chemicals and gases (oxidization) to cause smog. (EPA)

Pacific Decadal Oscillation (PDO). A pattern of Pacific climate variability that shifts phases on a multi-decadal time scale, usually about 20 to 30 years. The PDO is detected as warm or cool surface waters in the Pacific Ocean, north of 20° N. During a "warm", or "positive", phase, the west Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. (Wikipedia)

Pacific Northwest Index (PNI). Developed by Ebbesmeyer and Strickland (1995), PDI is a terrestrial climate index useful for studying climate effects on salmon productivity trends. It is a composite index that characterizes Pacific Northwest climate patterns in both coastal waters and freshwater habitats. In addition, it is a century-long record. A composite climate index is an effective measurement because many environmental parameters in the Northwest are statistically related to one another; consequently, they may be combined to furnish a broad-scale understanding of the state of the Pacific Northwest environment. The PNI uses three parameters: 1) air temperature at Olga in the San Juan Islands, averaged annually from daily data; 2) total precipitation at Cedar Lake in the Cascade Mountains; and 3) snowpack depth at Paradise on Mount Rainier on March 15 of each year. For each parameter, annual values are normalized by subtracting the annual value from the average of all years and dividing by the standard deviation. The sign of the normalized temperature is reversed because low temperature corresponds with high precipitation and snow. Finally, the three variables are averaged yearly giving a relative indicator of the variations in climate. Years with positive values of the PNI are warmer and drier than average and those with negative values are cooler and wetter than average. (ISAB)

Paleoclimate. Past or ancient climates. (NOAA Paleo)

Parameterize (Parameterization). In climate modeling, this term refers to the technique of representing processes that cannot be explicitly resolved at the resolution of the model (sub-grid scale processes) by the relationships between the area-averaged effect of such sub-gird scale processes and the larger scale flow. (IPCC)

Particulates. Tiny pieces of solid or liquid matter, such as soot, dust, fumes, or mist. (EPA)

Perfluorocarbons (PFCs). A group of human-made chemicals composed of carbon and fluorine only: CF4 and C2F6. These chemicals, specifically CF4 and C2F6, (along with hydrofluorocarbons) were introduced as alternatives to the ozone depleting substances. In addition, they are emitted as by-products of industrial processes and are also used in manufacturing. PFCs do not harm the stratospheric ozone layer, but they are powerful greenhouse gases: CF4 has a global warming potential (GWP) of 6,300 and C2F6 has a GWP of 12,500. (EPA)

Photosynthesis. The process by which green plants use light to synthesize organic compounds from carbon dioxide and water. In the process oxygen and water are released. Increased levels of carbon dioxide can increase net photosynthesis in some plants. Plants create a very important reservoir for carbon dioxide. (EPA)

Plankton. Small or microscopic organisms, including algae and protozoan that float or drift in great numbers in fresh or salt water, especially at or near the surface, and serve as food for fish and other larger organisms. (NOAA Paleo)

Planktonic Foraminifera. Marine zooplankton that passively float or weakly swim, and have calcium carbonate skeletons that are present in large numbers on the surface of the ocean. The skeletons of planktonic foraminifers are preserved in large numbers in deep-sea sediments, providing a rich fossil record of the environmental conditions of the upper ocean. The size of the shells is typically from 50 to 100 microns. (NOAA Paleo)

Pollen. Pollen grains that are made up of microspores containing a mature or immature male gametophyte. (NOAA Paleo)

Positive Feedback. A process that results in an amplification of the response of a system to an external influence. For example, increased atmospheric water vapor in response to global warming would be a positive feedback on warming, because water vapor is a GHG. (Pew)

Quaternary period. The second period of the Cenozoic era containing the Pleistocene epoch and the Holocene epoch and dating from 1.8 million years to the present. (NOAA Paleo)

Radiation. Energy emitted in the form of electromagnetic waves. Radiation has differing characteristics depending upon the wavelength. Because the radiation from the Sun is relatively energetic, it has a short wavelength (ultra-violet, visible, and near infra-red) while energy re-radiated from the Earth's surface and the atmosphere has a longer wavelength (infra-red radiation) because the Earth is cooler than the Sun. (EPA)

Radiative Damping. An imposed positive radiative forcing (q.v.) on the Earth-atmosphere system (e.g., through the addition of greenhouse gases) that represents an energy surplus. The temperature of the surface and lower atmosphere will then increase and in turn increase the amount of infrared radiation being emitted into space, thus establishing a new energy balance. The amount that emissions of infrared radiation to space increases for a given increase in temperature is known as the radiative damping.(IPCC)

Radiative Forcing. A change in the balance between incoming solar radiation and outgoing infra-red radiation. Without any radiative forcing, solar radiation coming to the Earth would continue to be approximately equal to the infra-red radiation emitted from the Earth. The addition of greenhouse gases traps and increased fraction of the infra-red radiation, reradiating it back toward the surface and creating a warming influence (i.e., positive radiative forcing because incoming solar radiation will exceed outgoing infra-red radiation). (EPA)

Radiocarbon age. The age of plant or animal remains determined by measuring the remaining activity of the 14C atoms in the sample: A=A0e-ltwhere A is the measured activity, A0 is the initial activity, l is the decay constant, and t is the sample age. (NOAA Paleo)

Relative dating. Dating methods that determine time with respect to stratigraphic position, for example deeper layers being older, or with respect to some changing quantity or property, such as magnetic polarity. (NOAA Paleo)

Residence Time. The average time spent in a reservoir by an individual atom or molecule. Also, the age of a molecule when it leaves the reservoir. With respect to greenhouse gases, residence time usually refers to how long a particular molecule remains in the atmosphere. (EPA) Reservoir. A component or components of the climate system where a greenhouse gas or precursor of greenhouse gas are stored. (Australia)

Respiration. The process by which animals use up stored foods (by combustion with oxygen) to produce energy. (EPA)

Salt Wedge. The layer of salt water that penetrates upriver under the freshwater layer to the head of the estuary. Because the estuary is deeper near the ocean, and shallows upstream, the layer is typically wedge-shaped

Sea surface temperatures. Temperature of the ocean's surface used in collaboration with other data to predict an El Niño occurrence. (NOAA Paleo)

Sink. A reservoir that uptakes a pollutant from another part of its cycle. Soil and trees tend to act as natural sinks for carbon. (EPA)

Soil moisture. Water stored in or at the continental surface and available for evaporation. In IPCC 1990 a single store (or bucket) was commonly used in climate modes. Today's models which incorporate canopy and soil process view soil moisture as the amount held in excess of plant "wilting point." (IPCC)

Solar Radiation. Energy from the Sun. Also referred to as short-wave radiation. Of importance to the climate system, solar radiation includes ultra-violet radiation, visible radiation, and infra-red radiation. (EPA)

Solar variability. Changes in the sun's radiation due to the sun's internal dynamics. (NOAA Paleo)

Southern Oscillation (ENSO). Shifting of pressure zones in the Pacific during an El Niño event. (NOAA Paleo)

Stratification. Increase in water density with depth caused by changes in salinity and/or temperature.

Stratosphere. The part of the atmosphere directly above the troposphere. See Atmosphere.

Sulfate Aerosol. Particulate matter that consists of compounds of sulfur formed by the interaction of sulfur dioxide and sulfur trioxide with other compounds in the atmosphere. Sulfate aerosols are injected into the atmosphere from the combustion of fossil fuels and the eruption of volcanoes like Mt. Pinatubo. Recent theory suggests that sulfate aerosols may lower the earth's temperature by reflecting away solar radiation (negative radiative forcing). Global Climate Models which incorporate the effects of sulfate aerosols more accurately predict global temperature variations. (EPA)

Sulfur Dioxide (SO2). A compound composed of one sulfur and two oxygen molecules. Sulfur dioxide emitted into the atmosphere through natural and anthropogenic processes is changed in a complex series of chemical reactions in the atmosphere to sulfate aerosols. These aerosols result in negative radiative forcing (i.e., tending to cool the Earth's surface). (EPA)

Sulfur Hexafluoride (SF6). A very powerful greenhouse gas used primarily in electrical transmission and distribution systems. SF6 has a global warming potential of 24,900. (EPA)

Thermal expansion. Expansion of a substance as a result of the addition of heat. In the context of climate change, thermal expansion of the world's oceans in response to global warming is considered the predominant driver of current and future sea-level rise. (Pew)

Thermocline. The region of the world's ocean, typically at a depth of lkm, where temperature decreases rapidly with depth and which marks the boundary between the surface and Deep Ocean. OPCC).

Thermohaline Circulation. Large-scale density-driven circulation I the oceans, driven by differences in temperature and salinity. (IPCC)

Trace Gas. Any one of the less common gases found in the Earth's atmosphere. Nitrogen, oxygen, and argon make up more than 99 percent of the Earth's atmosphere. Other gases, such as carbon dioxide, water vapor, methane, oxides of nitrogen, ozone, and ammonia, are considered trace gases. Although relatively unimportant in terms of their absolute volume, they have significant effects on the Earth's weather and climate. (EPA)

Tradewinds. A system of low-level winds occurring in the tropics; the tradewinds blow from the northeast to the equator in the Northern Hemisphere and from the southeast to the equator in the Southern Hemisphere. (NOAA Paleo)

Transient Climate Response. The tirne-dependent response of the climate system or model to a tirne-varying change of forcing. (IPCC)

Troposphere. The lowest layer of the atmosphere. The troposphere extends from the Earth's surface up to about 10-15 km. See also Atmosphere.

Tropospheric Ozone (O3). Ozone that is located in the troposphere and plays a significant role in the greenhouse gas effect and urban smog. See Ozone for more details. (EPA)

Turn-over time. The ratio between the mass of a reservoir (e.g. mass of N20 in the atmosphere) and the rate of removal from the reservoir (e.g. for N20, the rate of destruction by sunlight in the stratosphere (q.v.). (IPCC)

Uncertainty. Uncertainty is a prominent feature of the benefits and costs of climate change. Decision makers need to compare risk of premature or unnecessary actions with risk of failing to take actions that subsequently prove to be warranted. This is complicated by potential irreversibilities in climate impacts and long term investments. (Pew)

Upwelling. Rising of cold, nutrient-rich water towards the surface. (NOAA Paleo)

Urban Heat Island (UHI). Refers to the tendency for urban areas to have warmer air temperatures than the surrounding rural landscape, due to the low albedo of streets, sidewalks, parking lots, and buildings. These surfaces absorb solar radiation during the day and release it at night, resulting in higher night temperatures. (Pew)

Volatile Organic Compounds (VOC). Any one of several organic compounds which are released to the atmosphere by plants or through vaporization of oil products, and which are chemically reactive and are involved in the chemistry of tropospheric ozone production. Methane, while strictly falling within the definition of a VOC, is usually considered separately. (IPCC)

Water Vapor. The most abundant greenhouse gas, it is the water present in the atmosphere in gaseous form. Water vapor is an important part of the natural greenhouse effect. While humans are not significantly increasing its concentration, it contributes to the enhanced greenhouse effect because the warming influence of greenhouse gases leads to a positive water vapor feedback. In addition to its role as a natural greenhouse gas, water vapor plays an important role in regulating the temperature of the planet because clouds form when excess water vapor in the atmosphere condenses to form ice and water droplets and precipitation. (EPA)