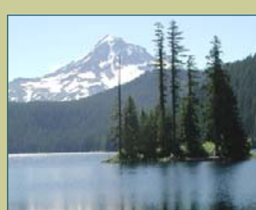
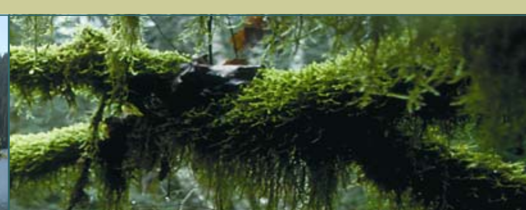


Climate Impacts on Washington's Hydropower, Water Supply, Forests, Fish, and Agriculture


A report by

Joseph H. Casola, Jennifer E. Kay, Amy K. Snover,
Robert A. Norheim, Lara C. Whitely Binder,
and the Climate Impacts Group

Center for Science in the Earth System
Joint Institute for the Study of the Atmosphere and Ocean
University of Washington

October 2005

This document was prepared at the request of King County (Washington) for the October 27, 2005 conference "The Future Ain't What It Used to Be: Planning for Climate Disruption" in Seattle, Washington. Information on that meeting is available at http://dnr.metrokc.gov/dnrp/climate-change/conference-2005.htm and http://www.cses.washington.edu/cig/outreach/workshops.shtml. For electronic copies of this document, visit http://www.cses.washington.edu/db/pubs/abstract459.shtml.

The Climate Impacts Group periodically updates its scenarios of Pacific Northwest climate change and climate impacts as warranted by developments in global climate models and improvements in regional modeling capabilities. For the most current scenarios, see http://www.cses.washington.edu/cig.pnwc/cc.shtml.

Cite as:
Casola, J.H., J.E. Kay, A.K. Snover, R.A. Norheim, L. C. Whitely Binder and the Climate Impacts Group. 2005. *Climate Impacts on Washington's Hydropower, Water Supply, Forests, Fish, and Agriculture*. A report prepared for King County (Washington) by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle).

Cover photo credits: Stream in the Olympic Peninsula (Climate Impacts Group); North Cascades Mountains (Climate Impacts Group); Wheat fields in the Palouse (Climate Impacts Group); Turbines inside powerhouse at The Dalles dam (Bob Heims, U.S. Army Corps of Engineers); Moss covered trees in the Hoh Rain Forest (Climate Impacts Group); Bull Run watershed (Tualatin Water District)

Table of Contents

Figures and Table

Figures

Table

Executive Summary

The climate is changing. Human activities, especially those related to fossil fuel combustion, have and will continue to change the composition of the atmosphere. Consequently, climate conditions in Washington during the 21st century will likely be different than those experienced in the past.

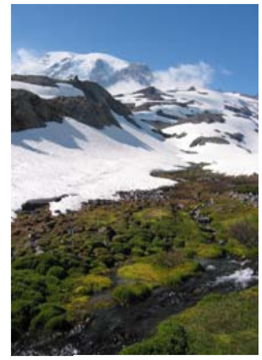
- All climate models project that temperatures will increase during the 21st century. The projected increases exceed the year to year variability in temperature experienced during the 20th century and occur across all seasons.

- Many climate models project a slight increase in precipitation, especially during the fall and winter months during the 21st century. However, natural year-to-year and decade-to-decade fluctuations in precipitation are likely to be more noticeable than longer term trends associated with climate change. Washington will probably continue to experience distinct periods, perhaps decades long, of relatively wet and relatively dry conditions.

Washington's economy and natural resources are sensitive to changes in climate. Management of hydroelectric power production, water supply systems, flood and storm management, forests, fisheries, and agriculture is predicated on observed patterns and extremes in temperature and precipitation. Each of these sectors has adapted to the timing and length of the seasons, the range of temperatures, and the amount and frequency of precipitation that has been experienced in the past. As temperature increases and precipitation patterns potentially change during the 21st century, current management practices may not achieve the results for which they are designed.

Hydroelectric Power Production

Increasing temperatures, decreases in snowpack, and shifts in the amount and timing of streamflow will likely reduce winter electricity demands and increase winter electricity generation. Conversely, summer demands are likely to increase overall while summer generation is likely to decrease. Any changes in annual hydropower generation are highly dependent on future changes in winter precipitation, and will probably be determined by the characteristics of future wet or dry cycles, the timing and intensity of which remain uncertain.



Melting snow at Mt. Rainier (Climate Impacts Group)

Municipal and Industrial Water Supplies

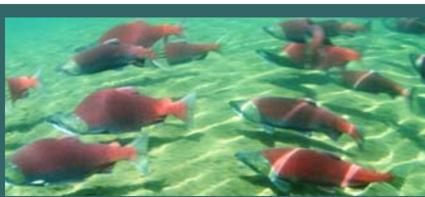
Increasing temperatures and decreased summer flows could make it more difficult for water suppliers to meet the needs of consumers and in-stream flow requirements, especially in snowmelt-fed watersheds.

Flood and Stormwater Management

Increasing temperatures and small increases in winter precipitation could lead to increases in the frequency of flooding in some river basins. It is unclear how urban stormwater flooding may change in the future, as modeling the behavior of individual storms, and their potential response to global warming, is currently beyond the capabilities of global climate models.

Forests

In response to increasing temperatures, some tree species will shift their geographic range, migrating to higher elevations and latitudes. Other species may be unable to adapt and their numbers will decline. Increasing temperatures will likely create favorable conditions for fire and pest outbreaks, which could become more frequent and severe.



Sockeye salmon (Climate Impacts Group)

Fisheries

Increasing stream and lake temperatures along with changes in the volume and timing of streamflow could create environmental conditions that are inhospitable to many Pacific Northwest cold water fish populations. Salmon, which represent some of the region's most important fish species, are at particular risk.

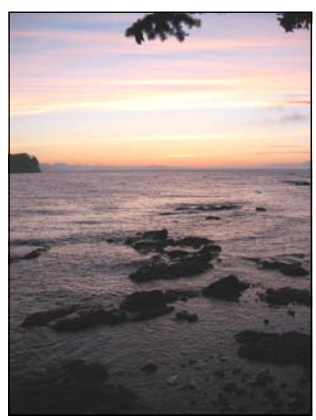
Agriculture

Increasing temperatures and atmospheric carbon dioxide concentrations will likely increase crop yields in places where sufficient soil moisture or irrigation water is available. However, in areas where soil moisture is projected to decrease, crops could suffer more days of heat and moisture stress. The shifts in the timing of peak streamflow could reduce the availability of irrigation water during the summer when it is needed the most. The increasing temperatures may also enhance threats posed by crop pests and pathogens.

Climate impacts on water resources are integral to each sector. The most important climate impact pathway for hydroelectric power production, water supply systems, flood and stormwater management, forests, fisheries, and agriculture involve changes in the timing and availability of water. The hydrologic changes will likely be most detrimental and acute during the summer, as water is projected to be less available, in many cases exacerbating existing conflicts over limited resources. Climate change will force resource managers and planners to evaluate complex tradeoffs between different management objectives and to adapt their systems to meet these objectives in an altered environment. In the Columbia River basin, for example, primacy for water management is currently reserved for flood control and hydroelectric power generation. In the future, integrated management decisions that incorporate trade-offs between hydroelectric power interests and other sectors such as in-stream flow augmentation will be required if those sectors' water needs are to be reliably met.

Planning should begin now. Although the climate changes occurring through the mid 21st are largely unavoidable, the ultimate consequences of those changes will depend strongly on today's decisions for preparation and adaptation. Furthermore, adaptation will take time, and planning and adaptation needs to begin well before (and in many instances several decades before) the impacts are expected to occur.

Today's choices will shape tomorrow's impacts. Not only will our choices about preparing for climate change determine Washington's resilience to future climate change, but choices we make today and into the future will help determine the total amount of change the global climate system will undergo. The rate of population growth, the type and amount of energy use, the development and spread of technology, and the rate and reach of globalization will all affect the rate at which greenhouse gases are emitted in the future and the rate at which the climate changes.



Sunset, Puget Sound (Climate Impacts Group)

Introduction

This booklet provides information on human-caused climate change ("global warming") and how it will affect Washington's natural resources, commerce, and industries. We focus on the anticipated climate changes taking place by the 2020s and 2040s and how they will impact **hydroelectric power production, municipal water resources, flooding and stormwater management, agriculture, forests, and fisheries**. This material is intended to assist natural resource managers, policy planners, and other decision makers in identifying which of their activities are sensitive and potentially vulnerable to climate change. The overarching message is that **the climate of the future is not likely to resemble the climate of the past, and planning for possible future climates should begin now.**

Global Climate Change

Human-induced climate change ("global warming") refers to the alteration of earth's energy balance resulting from the accumulation of greenhouse gases in the atmosphere. These gases, which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), act like a heat-trapping blanket that prevents the energy leaving the earth's surface from escaping to space and causes globally averaged temperatures to rise (*Figure 1*). This trapped energy can also cause potentially significant changes in the timing and length of the seasons as well as the amount and frequency of precipitation.

Because of human activities, atmospheric CO_2 concentrations are currently higher than any other time in the past 400,000 years and are likely to be higher than any time in the past 20 million years.[1] Fossil fuel burning is the primary source of anthropogenic (human caused) CO_2 emissions, accounting for three-quarters of today's emissions. The remainder of the CO_2 comes predominantly from land use changes such as deforestation.[2] Atmospheric concentrations of methane and nitrous oxide have also increased significantly. Methane's concentration has increased 151% since 1750, also exceeding any measurement for the last 400,000 years. Nitrous oxide's concentration has increased 17% since 1750, exceeding any level in at least the last 1,000 years.[3]

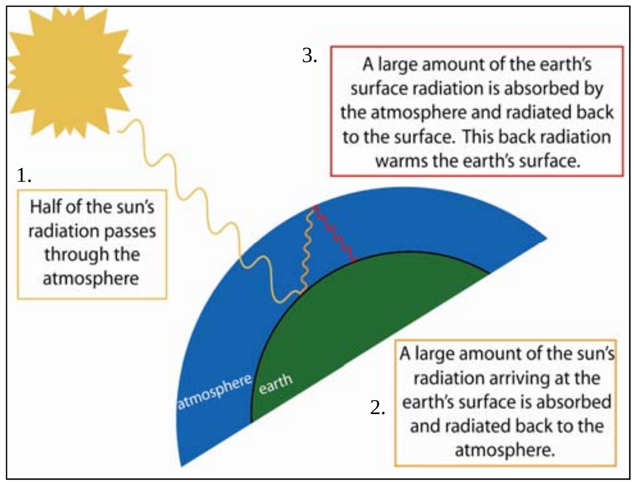


Figure 1. Accumulation of greenhouse gases in the atmosphere increases global mean surface air temperatures. The figure illustrates how greenhouse gases can prevent infrared radiation from escaping to space, acting like a blanket and warming the lower atmosphere. Figure source IPCC (2001)[4]

While the atmospheric burden of greenhouse gases has grown, globally averaged surface temperature has increased by 1.0 ± 0.4°F (0.6 ± 0.2°C) during the 20th century.[5] This warming represents the largest increase in temperature of any century in at least the last 1,000 years.[6] The warming has been uneven in time and space: nighttime temperatures have increased more than daytime temperatures, more warming has occurred at mid- and high latitudes than in the tropics, and more warming has occurred in the Northern

Hemisphere than in the Southern Hemisphere. As a result, the earth's physical systems have changed: glaciers have retreated; sea-ice has been reduced in thickness and extent; snow cover has decreased; and sea-level has risen, caused by both the expansion of warmer ocean water and the addition of water from melting ice sheets.[7] All of these temperature trends[8] and impacts are consistent with and provide evidence for the human-induced greenhouse gas warming. Although some of the past century's warming may be due to natural causes, most of the warming occurring between 1950 and 2000 can be attributed to greenhouse gases from human activities.[9]

Given the prevalence and necessity of fossil fuel combustion and the atmospheric persistence of greenhouse gases *(Table 1)*, atmospheric greenhouse gas concentrations will likely continue increasing through the 21st century and with that, global temperatures.

Precise projections of future greenhouse gas concentrations are highly uncertain; changes in emission patterns are dependent upon many factors such as population growth, energy use, the spread of technology, and the rate and reach of globalization.

Gas	Lifetime
Carbon Dioxide (CO_2)	5 to 200 years
Methane (CH_4)	12 years
Nitrous Oxide (N_2O)	114 years
Sulfur Hexafluoride (SF_6)	3,200 years
Carbon Tetrafluoride (CF_4)	50,000 years

Table 1: **Examples of greenhouse gas lifetimes.** The table shows some of the important greenhouse gases discussed in the text along with two synthetic gases (SF_6 and CF_4) that have long lifetimes. Lifetimes refer to the average amount of time an emitted gas will spend in the atmosphere before being chemically broken down, absorbed into the ocean or otherwise removed from the atmosphere. For CO_2, a single value cannot be assigned since there are many removal processes that occur at a range of speeds. Table source: IPCC (2001a)[10]

The international climate policy community has developed a suite of scenarios that make different assumptions about these social, political, and economic factors for the 21st century. The scenarios represent possible global futures, and there are no assigned probabilities to the scenarios' likelihood of taking place (i.e., three is not a "most likely" scenario). The scenarios' atmospheric concentrations for CO_2 range between 540 and 970 parts per million (ppm)[11] by 2100, representing at least a doubling from pre-industrial CO_2 concentrations (280ppm).

The magnitude of climate impacts for the 21st century varies by scenario. However, the scenarios do converge for many aspects of the climate:

- The 21st century will likely be warmer. The projected increase in global average temperature by 2100, relative to 1990, ranges from 2.5 to 10° F (1.4 to 5.8°C).[12] Loss of sea-ice and snow cover will likely continue along with increases in sea level.

- The frequency of extreme warm events and intense precipitation events are projected to increase. The interiors of many continents are projected to experience drier conditions, especially during the summers.

All of these changes will impact hydrological systems, ecosystems, agriculture, and human societies around the world.[13] Like the changes in climate observed over the last century, we can expect 21st century climate change to manifest itself differently at different times and in different places around the world. And since each part of the world has a unique set of environmental characteristics, key ecosystems, and patterns of dependence on natural resources, we can expect the impacts of those climate changes to differ significantly from place to place.

To understand how a specific region, such as Washington State, will be affected by climate change, we must examine the potential consequences of projected changes within the specific context of that place. The following sections provide an overview of projected climate change impacts on Washington state, paying particular attention to the important resources, ecosystems and climate sensitivities of this region.

References and Endnotes

[1] (IPCC) Intergovernmental Panel on Climate Change (2001a), J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* Cambridge University Press, Cambridge. Available for download at http://www.grida.no/climate/ipcc_tar/. Reference specifically from the Executive Summary.

[2] IPCC (2001a), Chapter 3, "The Carbon Cycle and Atmospheric Carbon Dioxide"

[3] IPCC (2001a), Executive Summary

[4] IPCC (2001a), Chapter 1, Figure 1.2

[5] IPCC (2001a), Executive Summary

[6] IPCC (2001a), Executive Summary

[7] More information regarding temperature trends and observed changes in the earth's physical systems can be found IPCC (2001a).

[8] Nighttime temperature, temperature over land (which is found disproportionately in the Northern Hemisphere), and temperature at higher latitudes where ice is present are more sensitive to greenhouse gas forcing than daytime temperature, temperatures over the ocean, and temperatures at lower, ice-free latitudes. These temperature trends act as important indicators of human-induced climate change.

[9] IPCC (2001a), Executive Summary; also, National Academies of Science (2001), *Climate Change Science: An Analysis of Some Key Questions,* Committee on the Science of Climate Change, Division on Earth and Life Studies, National Research Council, National Academy Press, Washington, D.C.

[10] Table information taken from IPCC (2001a), Technical Summary Table 1 and Table 6.7.

[11] IPCC (2001a), Executive Summary

[12] IPCC (2001a), Executive Summary

[13] (IPCC) Intergovernmental Panel on Climate Change (2001b), J.J. McCarthy, O.S. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* Cambridge University Press, Cambridge, Summary for Policymakers. Available for download at http://www.grida.no/climate/ipcc_tar/. Reference specifically from the Executive Summary.

Washington and Climate Change

Washington has already experienced changes in climate during the 20th century that are consistent with human-caused global climate change. The average temperature in the Pacific Northwest (PNW) increased approximately 1.5°F (0.8°C) over the last century;[1] snowpack has been declining over the last 80 years, especially at lower elevations;[2] the onset of snow melt and peak streamflows in snow-fed rivers has moved earlier in the year; and many species of plants are blooming earlier in the year.[3] Although direct observations are not available, hydrologic models indicate that spring soil moisture has also been increasing.[4]

Future Temperature Changes

Given expected increases in greenhouse gas concentrations, many of these changes are projected to continue. Perhaps most importantly, temperature is expected to continue to rise. **Washington is likely to face an increase in temperatures across all seasons.** Projections derived from global climate models[5] indicate that PNW average annual temperatures will likely increase 2.5 to 3.7˚F (1.4 to 2.1˚C) by the 2020s *(Figure 2)*. For the 2040s the increase is projected to be between 3.1 and 5.3˚F (1.7 to 2.9˚C).[6] These increases are much larger than the average

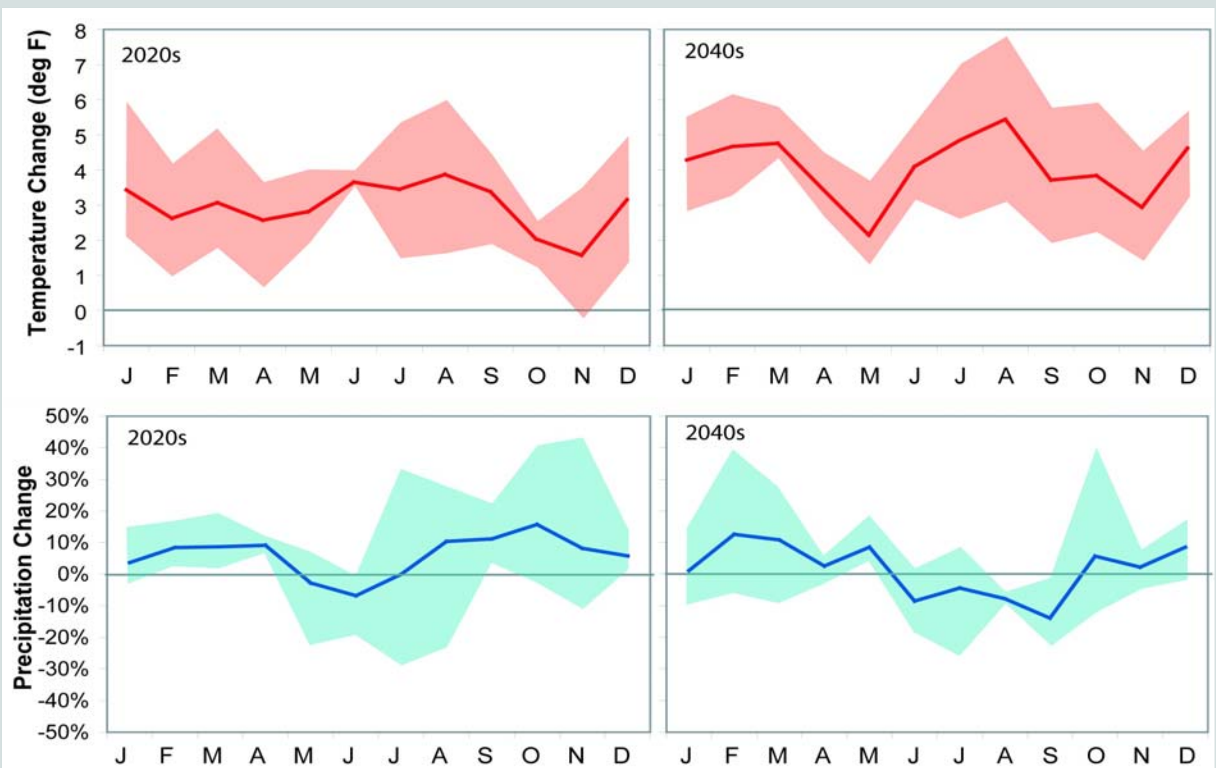


Figure 2. Projected changes in monthly temperature and precipitation in the Pacific Northwest for the 2020s and 2040s (in degrees F and percent). The red lines in the upper panels show the average change in temperature derived from four global climate models for the PNW for the 2020s and 2040s. The shaded regions represent the range of the models. Although there are differences among the model projections, all show increases in average temperature, regardless of the season. The blue lines and shaded regions show the average precipitation changes and ranges for the same models. The majority of the model projections call for wetter cool seasons (October-March) than the historical average. For the warm season (April-September), some models are relatively wet while others are relatively dry. The changes have been calculated relative to the 1990s.

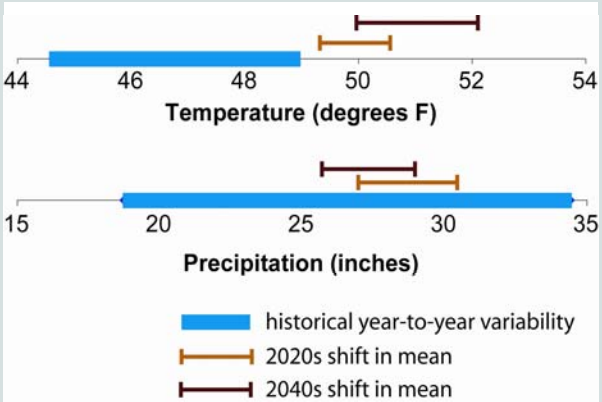


Figure 3. Comparison of historical year-to-year variations in temperature and precipitation with projected shifts in average temperature and precipitation. The blue bars represent the year-to-year variability in PNW temperature and precipitation during the 20th century. The orange and brown lines indicate the shift in average temperature and precipitation from four climate models for the 2020s and 2040s, respectively. Average temperature is projected to increase beyond the year-to-year variability observed during the 20th century, while future projected precipitation falls within the range of past variability.

increase experienced by the PNW over the last century *(Figure 3)*.

Future Precipitation Changes

Global climate models also provide a glimpse at Washington's future precipitation; however, this view is much less clear. Some models project increases in precipitation while others forecast decreases. The divergence in model projections results from the fact that precipitation is affected by complex, large-scale atmospheric circulation changes that are influenced by many imperfectly understood processes (e.g., ocean currents, tropical circulation, interactions between vegetation and the atmosphere).[7] Thus, projections for precipitation are more uncertain than for temperature.

Despite this limitation, **the majority of models project a wetter future, with most of the precipitation increases occurring in the cool season (October-March)** *(Figure 2)*.[8] Consistent with projected increases in temperature, a larger percentage of winter precipitation in the PNW is expected to fall as rain instead of snow. The models are divided as to whether the warm season (April-September) will be wetter or drier; however, any changes will be small given how little rain the region currently receives during the summer.

Overall, the projected precipitation changes will likely not be as drastic as the increases in temperature, relative to historic variability *(Figure 3)*. Thus, **natural year-to-year and decade-to-decade fluctuations in precipitation are likely to be more noticeable than longer term trends associated with climate change.** In other words, the projections for a systematically wetter winter climate do not imply that all years or decades will be wetter than average. **Washington will probably continue to experience distinct periods, perhaps decades long, distinguished alternatively by relatively wet and relatively dry conditions.**

In contrast to the historical record of temperature, which shows steady warming over most of the 20th century, the historical record for precipitation shows a variety of trends. While there is a robust increase in warm season precipitation across the West from 1916 to 2003, the cool season has displayed relatively wet and relatively dry periods. Precipitation statistics derived from Columbia River flow records indicate decreasing cool season precipitation from the late 1800s to the present. However, direct observations for the 1916-2003 period show a slight increase in cool season precipitation, largely a result of extensive drought in the early portion of the record during the 1930s and 1940s. Most recently, the 1947-2003 period shows a drying trend in cool season precipitation.

These observations underscore the challenge of drawing conclusions about long-term precipitation trends. They also suggest that further study is needed to determine the different atmospheric processes that control cool and warm season precipitation in the West on long time scales (decades to centuries). The degree to which any of the cool or warm season

Updated 2005 Climate Change Scenarios

Modeling the earth's climate system and projecting future climate change continue to be very active areas of research. Global climate models continue to evolve as additional scientific information and increased computing power becomes available. Researchers continue to develop future socioeconomic scenarios, each resulting in different scenarios for future greenhouse gas emissions. Methods for downscaling global climate change projections to the regional scale continue to be improved.

In preparation for the Fourth Assessment by the Intergovernmental Panel on Climate Change (due out in 2007), modeling centers around the world have prepared new simulations of future climate change, using updated global climate models and greenhouse gas emission scenarios. The Climate Impacts Group has acquired and downscaled this output to the Pacific Northwest using recently developed downscaling techniques.

The new projections for PNW climate change ("2005 scenarios") show smaller temperature increases *(Figure 4)*. The 2005 scenarios also show slightly drier conditions for the 2020s and similar precipitation changes for the 2040s compared to the climate change scenarios described in this paper. These differences are primarily due to the examination of a much larger set of global climate models and a new and improved standardization method (for establishing the baseline to which future changes are compared). The new baseline for all model projections is the 1970-2000 mean climate.[9]

The implication of cooler 2005 scenarios is that temperature increases will occur a decade or more later in the century than previously projected. As a result, climate impacts that depend on these temperature changes (such as reductions in snowpack *(Figure 6)* would occur later in the century than projected here. Climate impact projections that relied on a relatively cool model, such as the potential for increased stream temperature and salmon stress shown in Figure 22, may not shift later in the year. For details about how the 2005 climate change scenarios would affect the hydrologic results described in this paper, please see ***Implication of 2005 Climate Change Scenarios for Hydrologic Impacts Box.***[10]

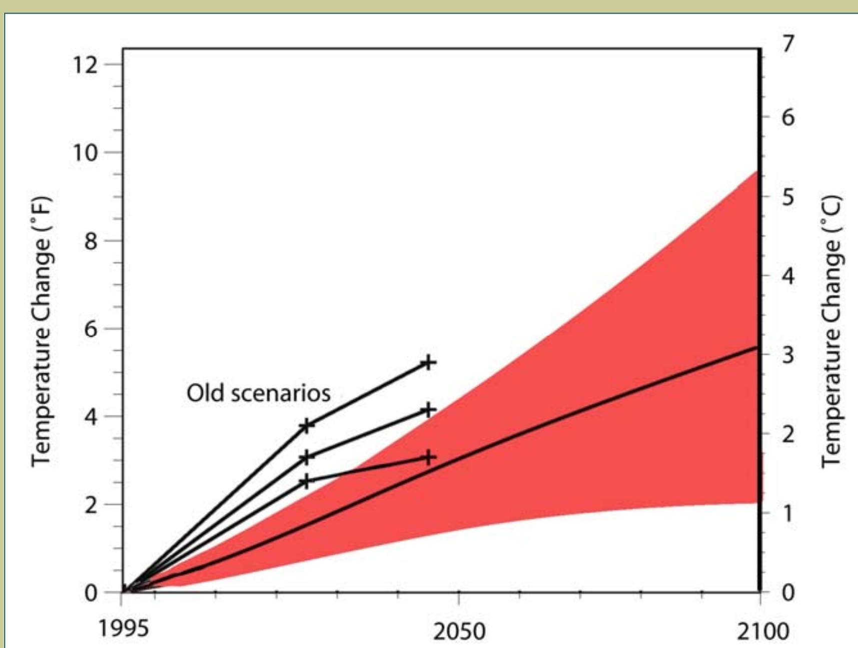


Figure 4. Comparison of projected changes in temperature for the Pacific Northwest for the 2005 and 2001 scenarios. The smooth black line shows the average temperature projections for ten climate models that use the 2005 scenarios. The red shading indicates the range of the models' temperature projections. The black line connecting plus signs (labeled "Old scenarios" represents the average and range for 2020s and 2040s temperature projections from four climate models using the 2001 scenarios. The projections made using the 2005 scenarios are cooler than the projections made using the 2001 scenarios, implying that many impacts may happen later in the 21st century than discussed in this report.

precipitation trends are a result of last century's warming, or how the trends might be affected by future warming, remains uncertain. The model projections for small increases in future precipitation, on the order of a few percent of the long-term precipitation average, should be understood as secondary to the larger, natural, decadal and multidecadal precipitation trends.

References and Endnotes

[1] Mote, P.W. (2003), Trends in Temperature and Precipitation in the Pacific Northwest During the Twentieth Century, *Northwest Science*, 77(4): 271-282.

[2] Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier (2005), Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western U.S., *Journal of Climate* (in review); also, Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier (2005), Declining Mountain Snowpack in Western North America, *Bulletin of the American Meteorological Society*, 86(1): 39-49; also, Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover (2003), Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest, *Climatic Change*, 61: 45-88.

[3] Cayan, D., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson (2001), Changes in the Onset of Spring in the Western United States, *Bulletin of the American Meteorological Society*, 82(3): 399-415.

[4] Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier (2005), 20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western U.S. *Journal of Climate* (in review). Available for download at ftp://ftp.hydro.washington.edu/pub/hamleaf/hamlet_runoff_trends/hamlet_west_wide_hydrologic_trends_070105.pdf.

[5] More information regarding the models and projections can be found in Kay, J.E., J.H. Casola, A.K. Snover and the Climate Impacts Group (2005), "Climate Impacts Science Primer", fact sheet prepared for King County (Washington)'s October 27, 2005 Climate Change Conference. This and other conference materials are available at http://www.cses.washington.edu/cig/outreach/workshops/kc2005.shtml. Temperature projections represent an average of projections from the ECHAM4, PCM, HadCM2, and HadCM3 global climate models. All show similar temperature increases, with the PCM representing the "coolest" model.

[6] Mote, P.W., A.F. Hamlet, and R. Leung (2005a), Possible Future Climate, Chapter 5 in A. K. Snover, E.L. Miles, and The Climate Impacts Group, *Rhythms of Change: An Integrated Assessment of Climate Impacts on the Pacific Northwest*, Cambridge, Massachusetts: MIT Press. (in review)

[7] Precipitation projections represent an average of projections from the ECHAM4, PCM, HadCM2, and HadCM3 global climate models. The HadCM2 model is relatively wet, while the ECHAM4 is relatively dry.

[8] For more information about future precipitation projections, see Mote et al. (2005a), "Possible Future Climate"

[9] For more information about these models, evaluation of their skill at simulating PNW 20th century climate, and their projections for 21st century PNW climate, see Mote, P. M., E. Salathé and C. Peacock. (2005b), *Scenarios of future climate for the Pacific Northwest*, Report prepared for King County (Washington) by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle).

[10] The Climate Impacts Group will continue to periodically update its scenarios of Pacific Northwest climate change and climate impacts as warranted by developments in global climate models and improvements in regional modeling capability. For the most current scenarios, see http://www.cses.washington.edu/cig/pnwc/cc.shtml.

Impacts on Washington's Hydrology

Many of the resources and industries discussed in this booklet intersect in their reliance on water. Hydropower is generated by water flowing in rivers and released from reservoirs. Cities require supplies of clean drinking water. Fish rely on clean water at an appropriate temperature for their habitat. Forests and crops rely on water to grow and reproduce. Droughts and floods can strain all of these water users, imposing significant conflicts among them.[1]

Snowpack

An important "natural" water reservoir is provided by snowpack that accumulates during the winter in mountain watersheds. During the 20th century, especially since 1945, snowpack has been declining throughout the West, with the Cascades showing some of the largest losses *(Figure 5)*.[2] Increases in temperature over the last 80 years have been shown to be the predominant cause of the observed declines in snowpack.[3]

Declines in Washington's mountain snowpack occurring over the last 80 years will likely continue due to warming, especially at lower elevations. Although future winters may be somewhat wetter on average, warmer temperatures should make more precipitation fall as rain and less as snow, resulting in reduced spring snowpack and earlier snowmelt *(Figure 6)*. Parts of Washington state where winter temperatures are currently near freezing would be the most sensitive to this climate change; in the warmest areas, significant snow accumulation in spring may

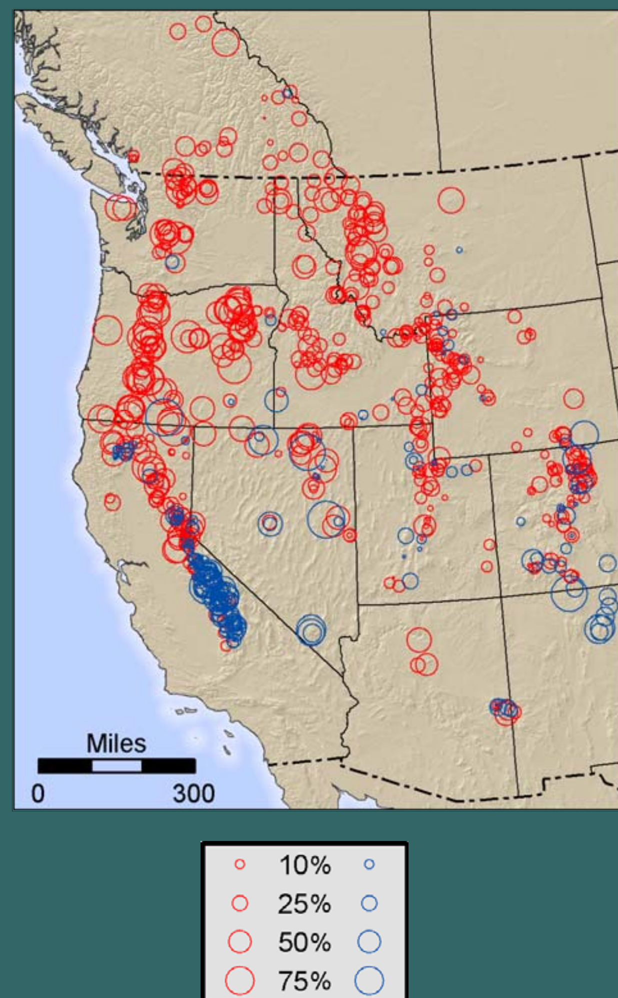
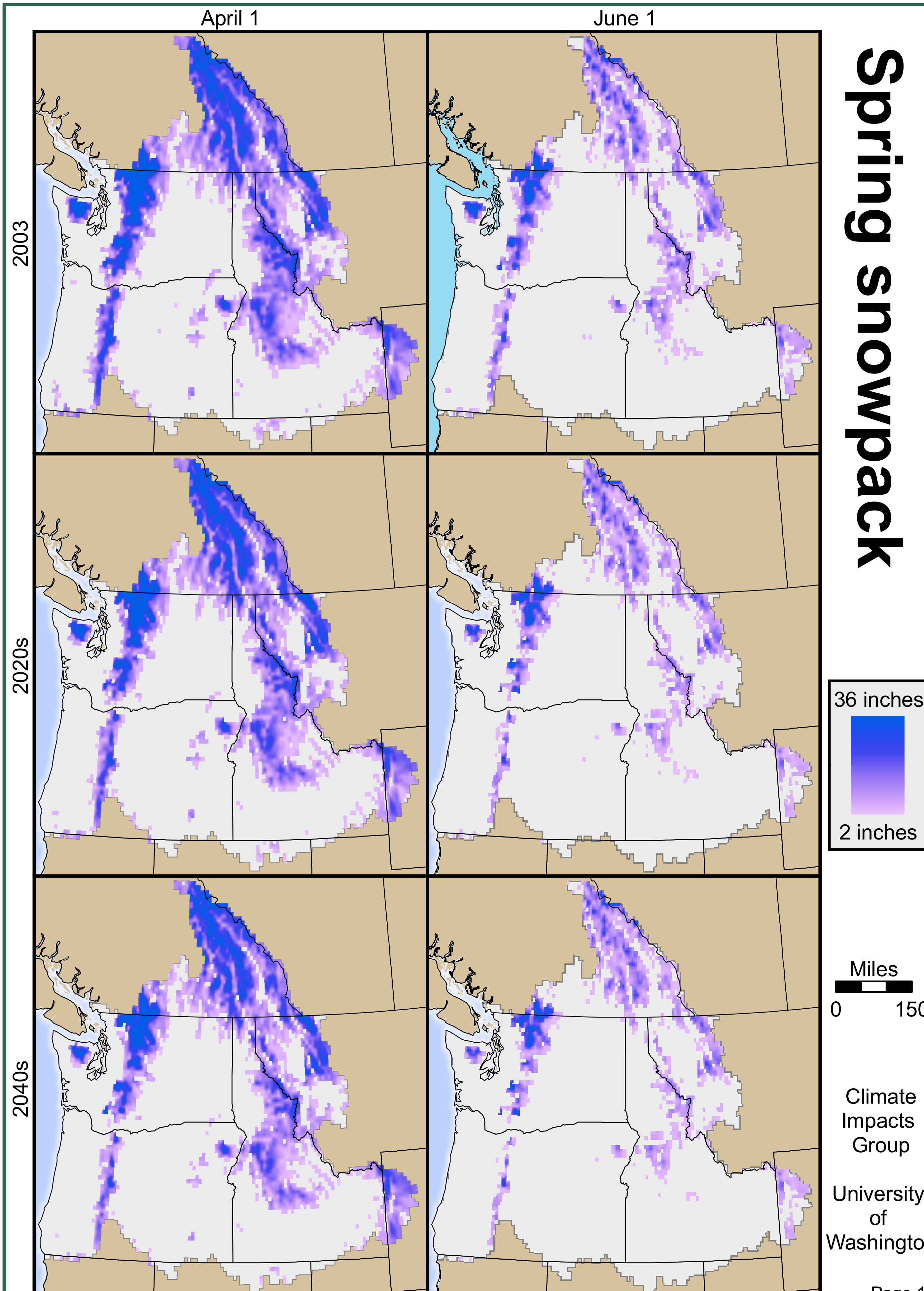


Figure 5. Changes in April 1 Snow Water Equivalent in the western United States. Linear trends in April 1 snow water equivalent (SWE) relative to 1950 at 798 snow course locations in the western U.S. and Canada for the period 1950-1997. Negative trends are shown by red circles and positive by blue circles. SWE is a common measurement for the amount of water contained in snowpack if it were melted instantaneously. Figure adapted from Mote et al. (2005).[4]

(Opposite page) **Figure 6. Spring snowpack (inches of snow water equivalent) in the Pacific Northwest for the 20th century, the 2020s, and the 2040s.** Areas in white are snow-free; areas in pink have some snowpack; areas in purple have relatively heavy snowpack. Future projections indicate that less snow is likely to accumulate during the winter and the snow melt is likely to occur earlier in the year. The projections have been made with an average of four climate models, one relatively wet model, one relatively dry model, one relatively warm model, and one relatively cool model. This four model composite can be considered a "middle-of-the-road" projection.

Spring snowpack



Climate Impacts Group

University of Washington

Skiing in the Pacific Northwest

The increases in temperature projected for the next century could pose serious challenges to skiing operations located in the Cascade Mountains. Many skiing areas may have to open later in the season, due to the later establishment of a sufficient base, while facing a shorter ski season and more frequent rainy days, all of which could negatively affect revenue. The most dramatic impacts would likely occur in lower elevation ski areas where current winter temperatures are often close to freezing.

The Climate Impacts Group (CIG) has performed model simulations to investigate how ski conditions in the Cascades would be affected by climate change.[5] Their work focused on three ski areas (Stevens Pass, Snoqualmie Pass, and Mission Ridge), examining three metrics of ski season: the percentage of years the ski area could open by December 1, the length of the ski season, and the number of rainy days during the ski season.[6]

This study showed that impacts are larger the lower the ski area's elevation and the warmer the climate *(Figure 7)*. A temperature change of 3.6°F (2°C) (projected to occur around the 2020s), could reduce the season length by 28% and 14%, for Snoqualmie and Stevens, respectively (compared to the 1948-1997 control climate). Quality of skiing conditions could also be reduced, with the percentage of rainy days during the ski season climbing above 50% for both locations. A temperature change of 4.5°F (2.5°C) (projected to occur around the 2040s) would further shorten the ski season and reduce the probability of opening by December 1 to less than 25% for both areas.[7] In short, the warmer it gets, the larger the magnitude of impacts.

Mission Ridge, located on the east side of the crest of the Cascades, would experience a slight increase in days of rain - around 40% of ski season days for both scenarios (compared with 25% in the control climate). However, due to Mission Ridge's higher elevation (its base is 4500 feet [1372 m]; for comparison, Snoqualmie is at 3000 feet [915 m] and Stevens is at 4060 feet [1238 m]) the length of the ski season and probability of opening would not be significantly affected. Higher elevation areas like Mission Ridge are probably more vulnerable to precipitation variability than regional warming.

It is important to note that the impacts of regional warming on the ski industry are not necessarily all negative. For example, warmer temperatures and less snow on the highways during the ski season could improve customer access to ski areas.

Figure 7. Projected changes in ski conditions at Snoqualmie Pass, Stevens Pass, and Mission Ridge for the 2020s and 2040s. Each graph shows how Cascade ski operations would be impacted by projected climate change. For all areas, future warming would likely make opening by December 1 more difficult, shorten the length of the ski season, and reduce the quality of ski conditions (as measured by the number of days where rain falls while the area is open). The areas at lower elevation (Snoqualmie and Stevens) are impacted the most. For all areas, impacts become worse as the warming increases.

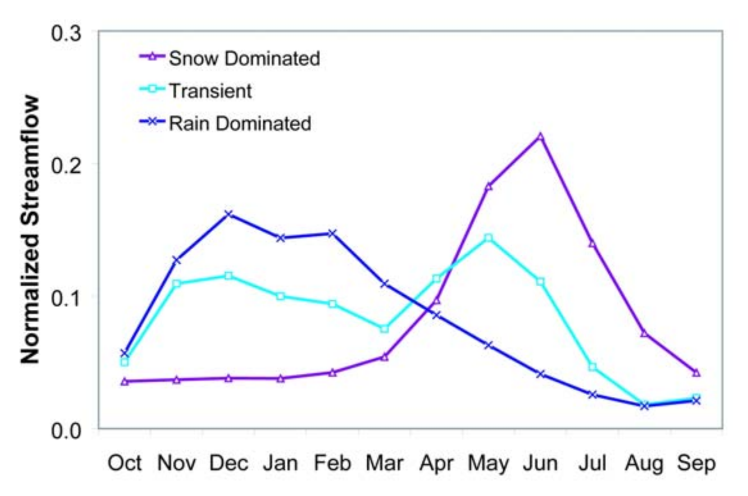


Figure 8. Typical seasonal streamflow patterns for a rain-dominant, snow-dominant, and transient watershed. Rain-dominant watersheds (dark blue line) typically experience peak flow during the winter, when precipitation is heaviest. Snow-dominant watersheds (purple line) have more area at higher elevation and accumulate snow during the winter. Their peak flows occur during the late spring or early summer as the snow melts. Transient watersheds (light blue line) receive both rain and snow during the winter, and display a double-peak in their hydrographs. Transient watersheds are the most sensitive to temperature increases.

become infrequent in the future. Meanwhile, all elevations - even those well above the current freezing level - would experience an earlier onset of snowmelt due to spring warming.

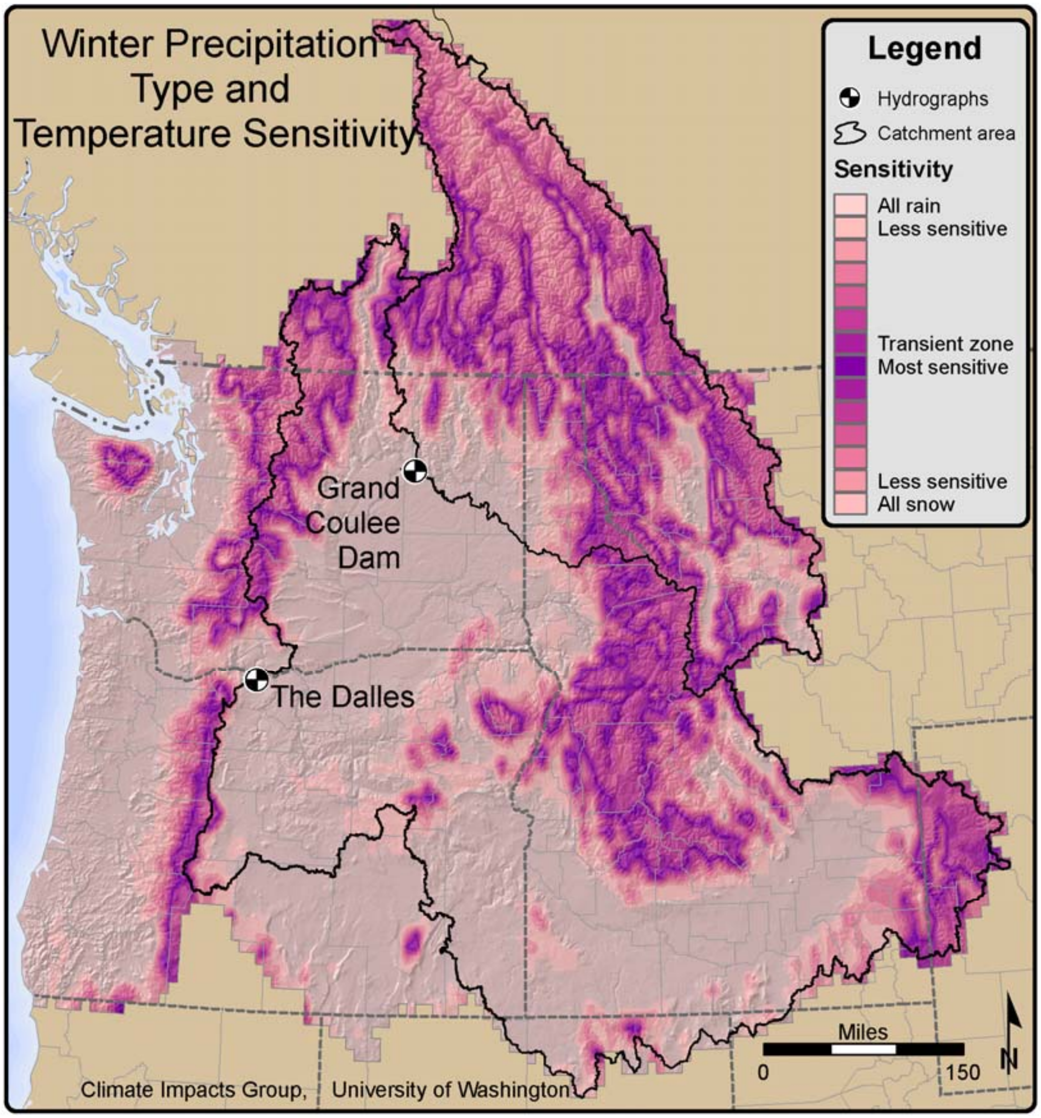
Streamflow

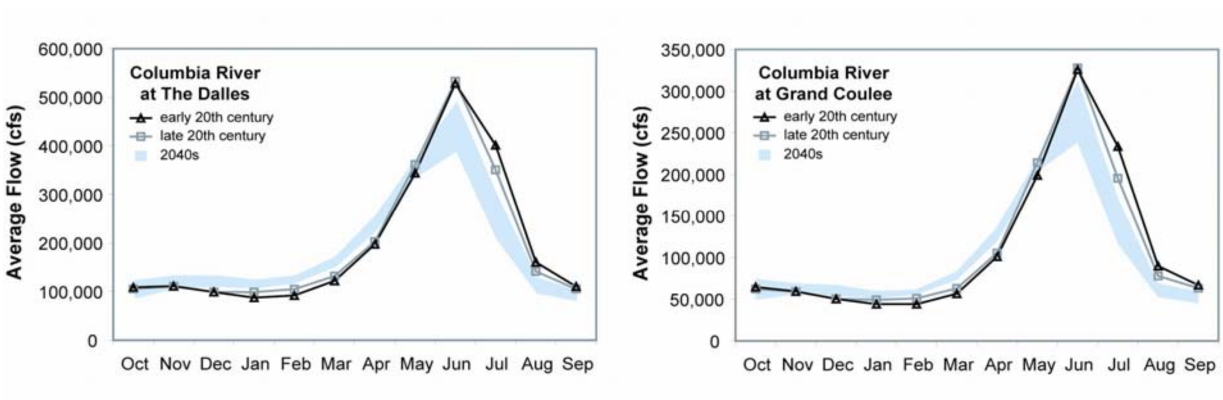
Streamflow varies strongly throughout the year as a result of seasonal cycles of precipitation, snowpack, temperature, and groundwater. Humans and ecosystems have adapted to the "rhythms" of streamflow occurring in the watersheds upon which they rely. **Changes in temperature and precipitation will likely affect the timing and volume of streamflow. However, a river system's precise response will depend on its elevation** *(Figure 8)*:

- Coastal rivers at low elevation exhibit flow behavior that follows seasonal precipitation patterns, with high flows during the wet winter months and low flows during the summer. These "rain-dominant" watersheds, like the Hoh River, respond directly to changes in precipitation. Projected increases in cool season precipitation could lead to increases in fall and winter flows. It is difficult to make projections for summer flow given the uncertainty in summer precipitation projections.

- Rivers fed by high elevation sources, such as those in the Columbia River Basin, are considered "snow melt-dominant" (the hydrographs for the Dalles and Grand Coulee Dam in Figure 9(a) are typical of a snow melt dominant system). These watersheds experience low flows in the winter, peak flows during the spring and early summer as snowpack melts, and low flows during the late summer. The timing of this cycle is sensitive to temperature. Projected temperature increases will likely increase winter flows, reduce spring and summer flows, and shift peak runoff earlier in the year, continuing and amplifying trends observed throughout the West over the last 80 years.[8]

- River systems at intermediate elevations, such as the Cedar, Tolt, Quinalt, and Spokane Rivers (see Figure 9(b)), experience mid-winter temperatures close to freezing and are sensitive to changes in the percentage of winter precipitation falling as snow. Typically, rivers in the "transient snow zone" have peak flows in November and December during periods of heavy precipitation and another period of peak flow during the spring as snowpack melts. Similar to snowmelt-dominant watersheds, the transient watersheds will likely have an enhanced winter time peak flow due to the increase in rain, reduced spring and summer flows due to the reduction in snowpack, and an earlier snow melt.[9] A small





Figures 9(a) and (b). Winter precipitation sensitivity to warming and projected streamflow changes in the Pacific Northwest. Areas where current winter precipitation is a mix of rain and snow are highly sensitive to future warming. These areas appear purple on the map; areas where winter precipitation is predominantly snow or rain are shaded pink. Solid black lines indicate the drainage area for the Columbia River Basin. The hydrographs below the maps show monthly naturalized streamflow (streamflow corrected for the effects of dams and withdrawals). The black line represents streamflow for typical hydrologic conditions and early 20th century temperature; the gray line represents calculated streamflow for typical hydrologic conditions but late 20th century temperature; the blue swath represents the range of projected streamflow for the 2040s.

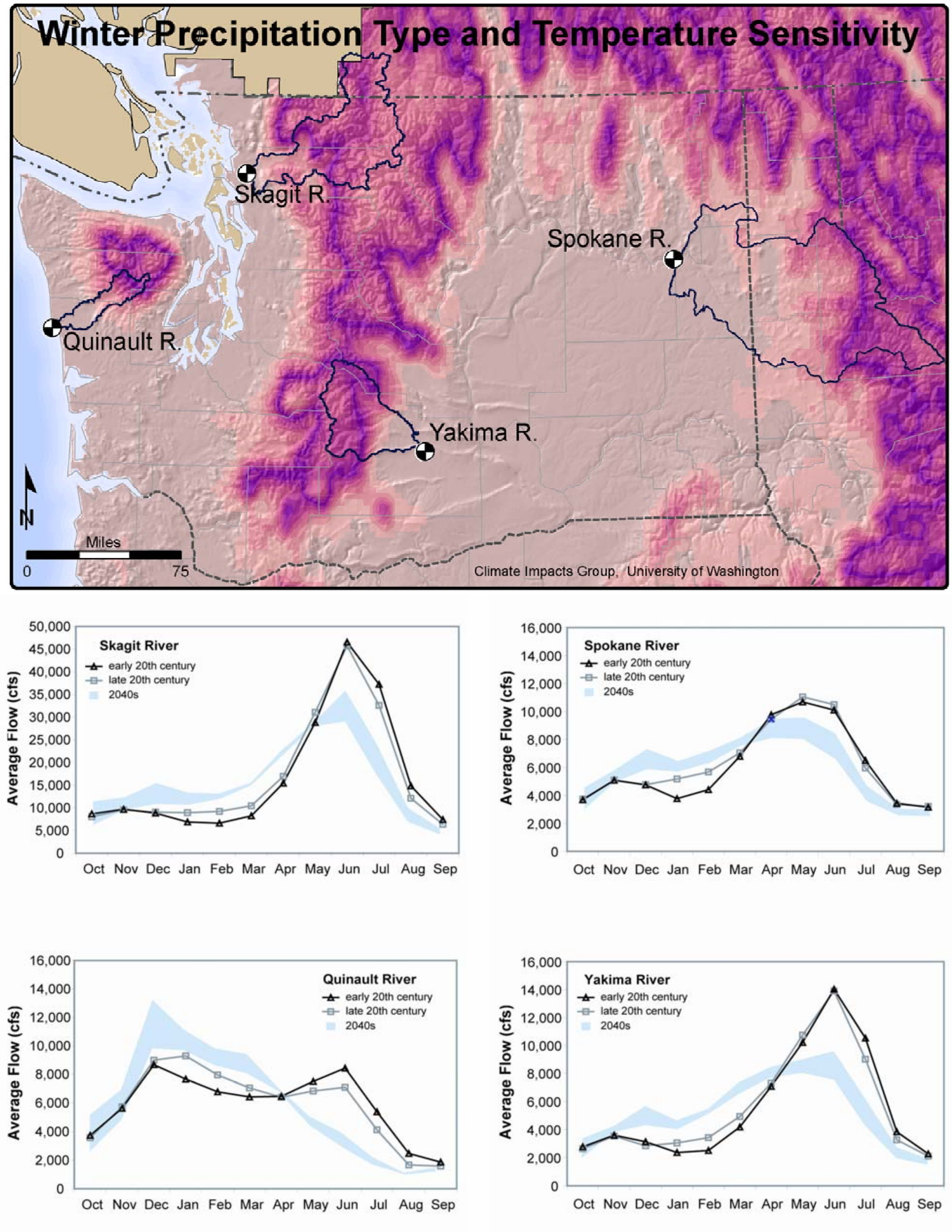


Figure 9(b). Winter precipitation sensitivity and projected changes in monthly streamflow for selected Washington State river basins.

amount of temperature increase in transient watersheds can lead to a large streamflow response, as demonstrated by the large changes in streamflow timing for the Spokane River at Long Lake.

Stream Temperatures

Many aquatic organisms have a particular temperature range in which they can function. Many factors, such as ground water flow, streamflow, vegetation along the banks, or nearby snow cover can affect water temperature. All of those factors being equal, water temperatures in unregulated rivers (those rivers whose flow is not controlled by dams)[10] tend to strongly influenced by air temperatures (*Figure 10*). During the typical summer low flow period that occurs across Washington State, streams are particularly susceptible to reaching high temperatures that can be dangerous for fish and other riverine life.

It is highly likely that projected increases in air temperature will lead to warmer stream temperatures, especially during the summer. Recent work on the Fraser River in British Columbia, an unregulated river, indicates that stream temperatures in the next century could be significantly higher during the summer *(Figure 11).*[11] Results from model simulations similar to those used in the results presented here demonstrate that dangerously high temperatures for fish on the Fraser could be exceeded during 20% of the summers by 2020, over 40% of the summers by 2050, and nearly 60% of the summers by 2080.[12] Water temperatures in the Columbia, although complicated by the presence of dams and reservoirs, are also expected to increase.

Soil Moisture

Soils of the PNW store large volumes of water, constituting a crucial water supply for vegetation and dry land agriculture. Soil moistures are usually lowest at the beginning of October.[13] Cool temperatures accompanied by heavy fall and winter precipitation allow the soil to accumulate water throughout the

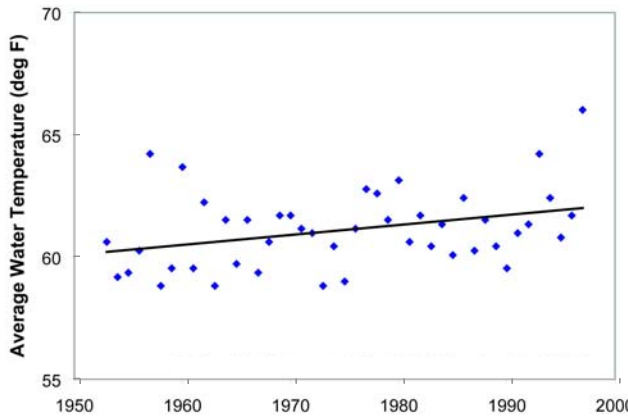


Figure 10. Warming trend in Fraser River average summer stream temperatures, 1953-1998. Each diamond represents the average summer stream temperature in the Fraser River (British Columbia). The black line shows the warming trend during the 35-year period. The warming trend likely reflects to response of unregulated rivers to increasing air temperatures. Reproduced with permission from the Pacific Salmon Commission and the British Columbia Ministry of Water, Land, and Air Protection.[14]

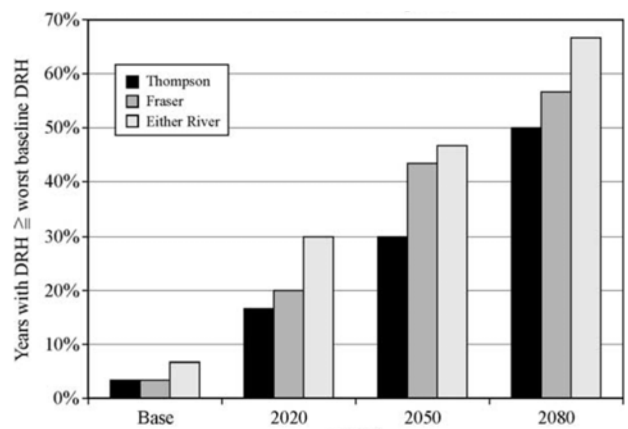
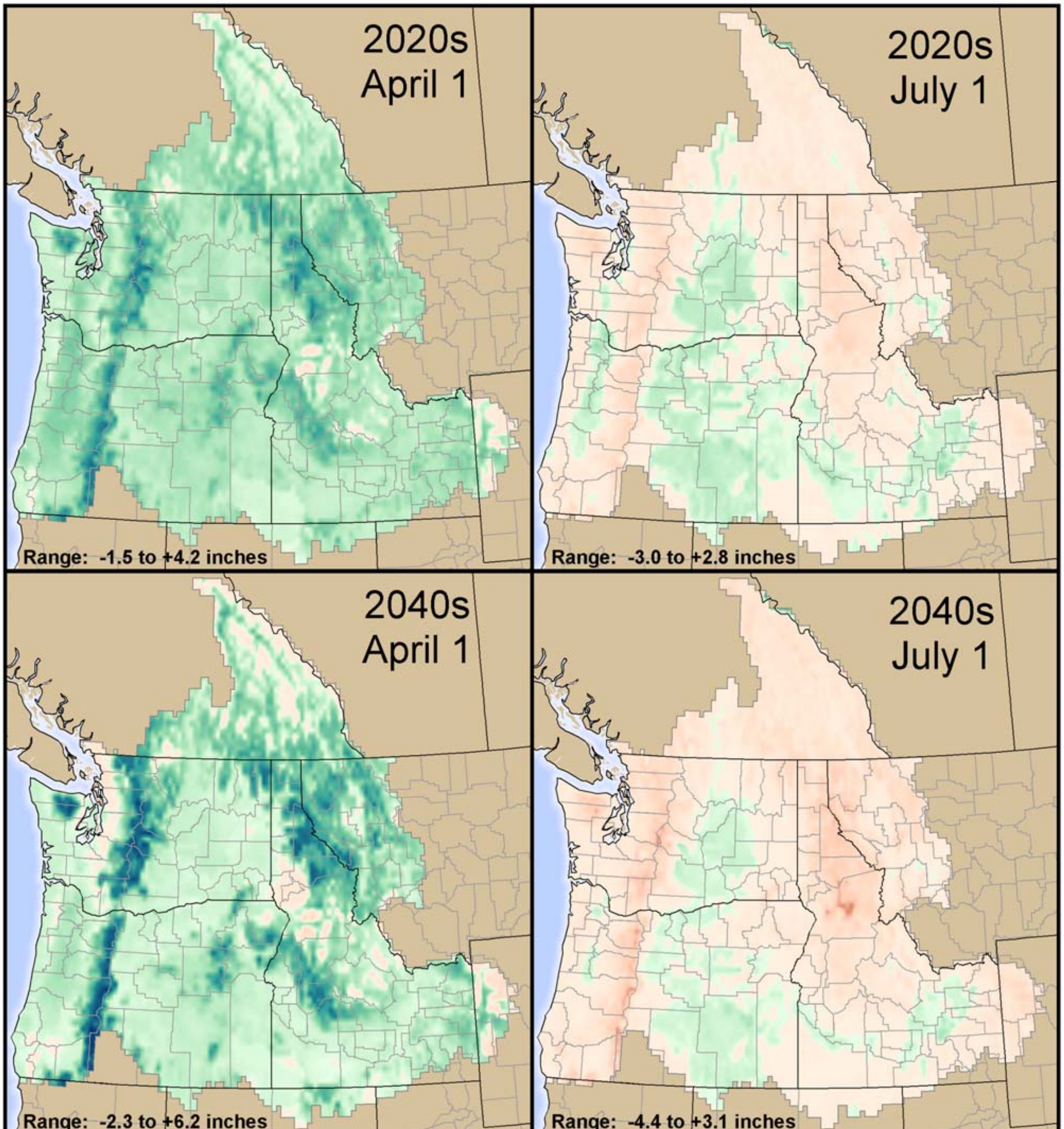


Figure 11. Historical and projected incidence of stream temperatures harmful to salmon spawning in the Fraser River watershed. The figure shows a dramatic projected increase in the frequency of high stream temperatures for the Fraser and Thomson Rivers, both located in the Fraser Watershed. The Thomson River flows into the Fraser – fish spawning in the Thomson may be harmed by high stream temperatures on either river, hence the "Either" column on the graph. The incidence of high stream temperatures is measured in DRH (Degree Reach Hours), which represents the number of hours during the summer along a 6 miles (10 km) portion of the river where stream temperatures exceed 68°F (20°C). The percentages plotted correspond to the number of years the DRH value was greater than the worst summer during the period 1961-1990. The label "2020" corresponds to the 30-year period 2010-2039; "2050" corresponds to 2040-2069; and, 2080 corresponds to 2070-2099. Reproduced with permission from Morrison et al. (2002).[15]



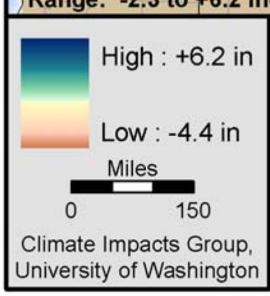


Figure 12. Projected changes in spring and summer soil moisture for the 2020s and 2040s. The four maps show projected soil moisture differences between future climate and the current climate. The left panels show differences for April 1 soil moisture. The differences for the 2020s appear on the top, the differences for the 2040s appear on the bottom. The right panels show similar maps for July 1 soil moisture. Increases in soil moisture relative to the current climate appear in green, decreases appear in brown. The April 1 projections show substantial increases in soil moisture for both time periods, a consequence of an earlier onset of snowmelt. The July 1 projections show small increases and decreases in soil moisture across the region. There appears to be moderate drying west of the Cascades and slight increases in soil moisture east of the Cascades; however, the July 1 projections are highly uncertain.

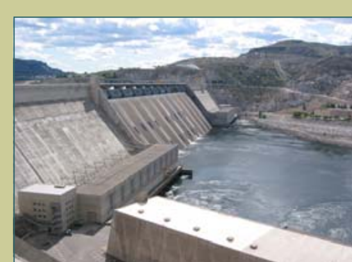
winter in areas that are above freezing. Soils in snow dominant watersheds tend to accumulate moisture later in the year with the onset of snowmelt. In most cases, soil moisture peaks in the spring or early summer. In summer, the longer days, decreased cloud cover, low precipitation, increased plant growth, and higher temperatures lead to a depletion of soil moisture over much of the PNW. The return of fall rains and cooler temperatures allow the soils to recharge, continuing the cycle.[16]

Under climate change scenarios, **increasing temperatures, reduced snow pack, and an earlier onset of snowmelt cause soil moisture recharge to occur earlier in the year in snowmelt-dominant and transient watersheds** *(Figure 12, left panels)*. Changes in soil moisture in the summer and fall are more difficult to predict, since they are sensitive to changes in many factors including solar radiation (cloudiness), wind speed, precipitation, humidity, and temperature. **For areas west of the Cascades where evaporation rates are an important factor in determining seasonal evaporation, warming would tend to enhance soil drying and reduce soil moisture in the summer and fall** *(Figure 12, right panels)*. **East of the Cascades, where warm season evaporation in natural settings is almost entirely determined by water availability, summer soil moistures will likely be most sensitive to precipitation changes.** If summer precipitation increases, soil moistures in natural landscapes may be similar to those observed today, or may even increase.

IMPLICATION OF 2005 CLIMATE CHANGE SCENARIOS FOR HYDROLOGIC IMPACTS

New projections for Pacific Northwest climate change ("2005 scenarios") are slightly cooler and, in the 2020s, drier than the climate change scenarios used in the hydrologic studies described in this paper (see ***Updated 2005 Climate Change Scenarios Box***). The 2005 scenarios could affect the hydrologic results described in this paper as follows:*

- Under the cooler (2005) climate change scenarios temperature related effects including decreases in snowpack, increases in April soil moisture, streamflow timing shifts from summer to winter, and water resources impacts associated with earlier peak flow and decreased summer water availability that were previously projected for the 2020s and 2040s would occur later in the century.
- The electricity demand changes projected by the Northwest Power and Conservation Council for the 2020s and 2040s would similarly occur later in the century due to the cooler 2005 climate change scenarios.
- Increases in annual streamflow volume (which are controlled primarily by winter precipitation changes) previously projected for the 2020s are probably overestimated, given the drier projections of the 2005 scenarios.
- For the 2040s, projections of annual streamflow volume changes would be comparable under both the old and new (2005) climate change scenarios due to the similarities in their projected precipitation changes.



Grand Coulee Dam, Washington (Source: Climate Impacts Group)

* For more information on how the 2005 scenarios would affect various previous hydrologic studies, see Lettenmaier et al. (2005), *Implications of 2005 climate change scenarios for Pacific Northwest hydrologic studies*.[17]

References and Endnotes

[1] Hydrologic projections for snowpack, streamflow, and soil moisture were made using four global climate models (ECHAM4, PCM, HadCM2, and HadCM3).

[2] The Cascades have experienced a decrease in April 1 snowpack of nearly 30% when comparing the winters for 1945-1955 to the winters for 1990-1997. Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier (2005), Declining Mountain Snowpack in Western North America, *Bulletin of the American Meteorological Society*, 86(1): 39-49.

[3] Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier (2005), Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western U.S. *Journal of Climate* (in review); also Mote at al. (2005), "Declining Mountain Snowpack in Western North America"; also Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier (2005), 20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western U.S. *Journal of Climate* (in review). Available for download at ftp://ftp.hydro.washington.edu/pub/ hamleaf/hamlet_runoff_trends/ hamlet_west_wide_hydrologic_trends_070105.pdf

[4] Mote et al. (2005)

[5] Hamlet, A.F. (2000), *Effects of Climate Change on Ski Conditions at Snoqualmie Pass, Stevens Pass, Mission Ridge, and Schweitzer Mountain Ski Areas*, Final Technical Report. Hamlet (2000) employs the HadCM2 and ECHAM4 global climate models.

[6] "Opening" is considered possible when ~1m of snow lies at the ski area base. "Length of season" is equal to the average number of days between Oct 31 and March 31 where the ski area base is at least 1m. "Days of rain" are approximated by the percentage of days during the ski season when at least 0.5mm of rain falls while the ski area base is at least 1m.

[7] Results represent the average from two climate models, one relatively wet model (HadCM2) and one relatively dry (ECHAM4).

[8] Hamlet et al. (2005), "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western U.S."

[9] A more detailed discussion of hydrological changes, including changes in streamflow, can be found in Hamlet, A.F., and D.P. Lettenmaier (1999), Effects of Climate change on Hydrology and Water Resources in the Columbia River Basin, *Journal of the American Water Resources Association*, 35(6): 1597-1623. For discussion specific to transient watersheds, see VanRheenen, N.T., R.N. Palmer, and M.A. Hahn (2003), Evaluating Potential Climate Change Impacts on Water Resource Systems Operations: Case Studies of Portland Oregon and the Central Valley, California. *Water Resources Update*, 124: 35-50; and Hahn, M.A., R.N. Palmer, A.F. Hamlet, and P. Stork (2001), *Preliminary Analysis of the Impacts of Climate Change on the Reliability of the Seattle Water Supply*. Proceedings of the ASCE 2000 World Water and Environmental Resources Conference, Orlando, FL, May 20-24, 2001.

[10] Dams' impedance of flow can cause water temperatures to change, independent of climate.

[11] Morrison, J., M.C. Quick, and M.G.G. Foreman (2002), Climate Change in the Fraser River Watershed: Flow and Temperature Projections. *Journal of Hydrology*, 263: 230-244. For stream temperature research on the Taulatin River, a regulated river, see Palmer, R.N., N.T. VanRheenen, E. Clancy, and M.W. Wiley (2005), *The Impacts of Climate Change on the Tualatin River Basin Water Supply: An Investigation into Projected Hydrologic and Management Impacts*, A Report Prepared for Clean Water Services, Tualatin, Oregon, August, 2005. Recent work has begun on the Snohomish river as well (http://www.tag.washington.edu/ projects/sushi.html)

[12] Morrison et al. (2002), "Climate Change in the Fraser River Watershed: Flow and Temperature Projections", employ the CGCM1 and HadCM2 global climate models.

[13] Hydrologists and water managers consider October 1 the beginning of the water year and September 30 the end of the water year.

[14] Data source: Historical temperature data from the Pacific Salmon Commission, 1941-1998. Data available online at http://wlapwww.gov.bc.ca/soerpt/997climate/gsalmon.html.

[15] Morrison et al. (2002)

[16] More information regarding soil moisture can be found in Hamlet et al. (2005), "20th Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western U.S."

[17] Lettenmaier, D. P., M. W. Wiley, A. H. Hamlet and R. Palmer. (2005). *Implications of 2005 climate change scenarios for Pacific Northwest hydrologic studies.* Report prepared for King County (Washington) by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle).

Impacts on Hydropower

Hydroelectric power serves as one of Washington's most important natural and economic resources, accounting for approximately 66%[1] of the electricity generated in the state. The operation of these reservoirs and dams for production of hydroelectricity has been tuned to the historical seasonal variations in electricity demand and the timing and volume of streamflow. In the 21st century, however, **projected climatic and hydrologic changes will likely alter the annual patterns of electricity demand and streamflow, posing challenges to the current management of the PNW's hydroelectric power network**.

Demand for electricity typically peaks in the winter months in Washington when heating and lighting requirements are at a maximum due to the relatively short days and low air temperatures. Figure 13 shows the relationship between historical electricity consumption and temperature, demonstrating how Washington's energy consumption is at a minimum when seasonal temperatures are at a maximum, and vice versa.[2] This is a stark contrast to many other states where higher average summer temperatures and heavy reliance on air conditioning cause high consumption when temperatures are high.

Projected warming due to climate change will likely lower electricity demand during the winter and increase demand during the summer in Washington. Indeed, the gap between winter and summer electricity consumption has been shrinking in recent years, reflecting both the increased penetration of air conditioning and the relative warmth of the last decade. Published estimates *(Figure 14)* demonstrate

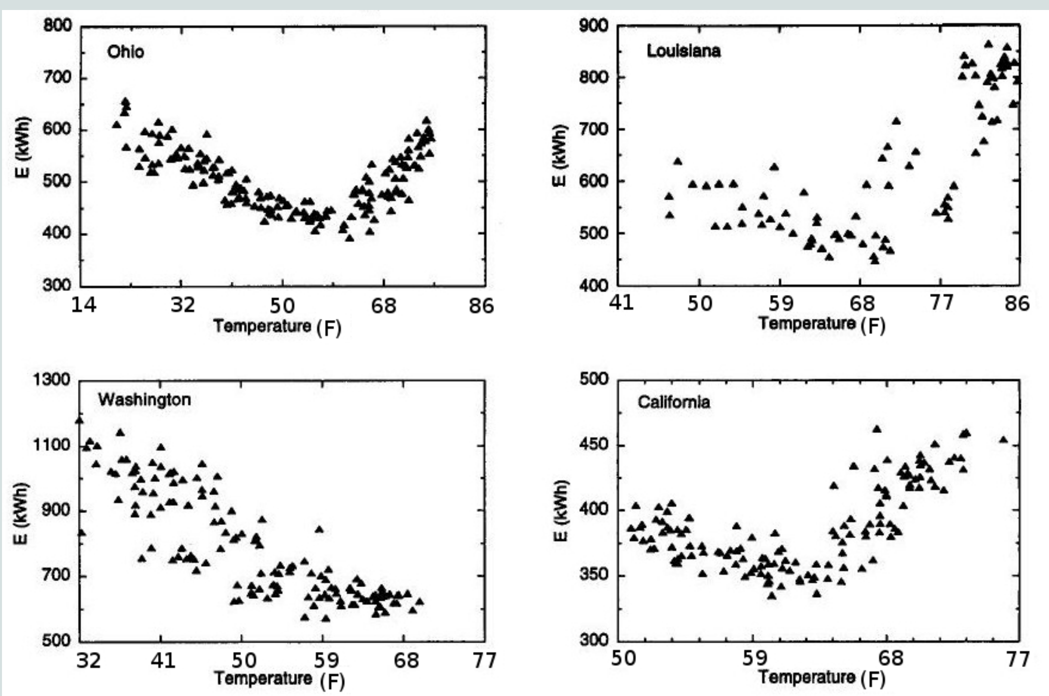


Figure 13. Residential and commercial per capita electricity consumption (kWh) and monthly average air temperature. Based on data for 1984-1994, most states show an increase in electricity consumption once monthly average temperatures surpass 68°F (20°C), most likely because of air conditioning. However, Washington's average monthly temperatures generally stay below this threshold, indicating that climate change could increase air conditioning and summer electricity demand. Reproduced with permission from Sailor et al. (1997).[3] Temperature values converted to degrees F.

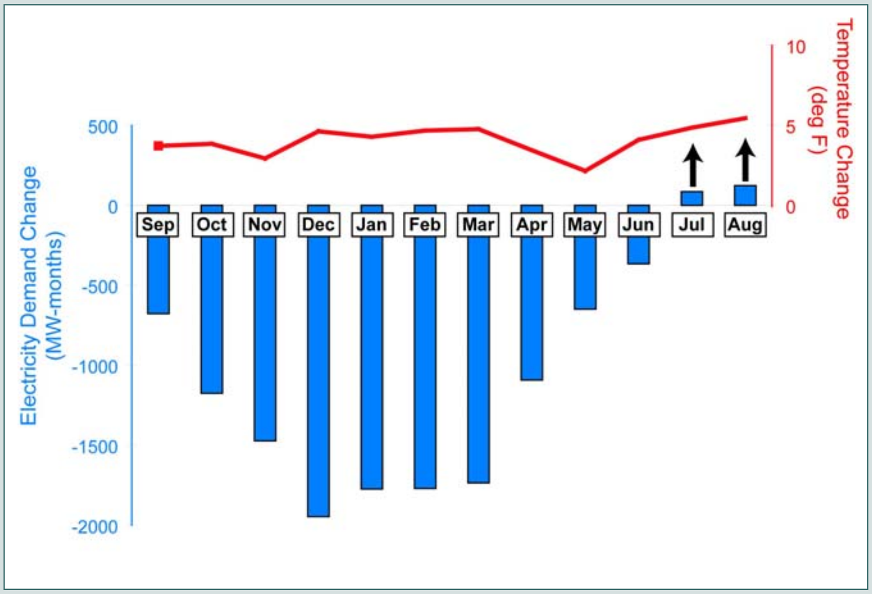


Figure 14. Projected 2040 monthly temperature increases (degrees F) and the estimated impact on electricity demand (megawatt-months). The red line shows the projected average temperature increase from four climate models for the PNW. Blue bars indicate the corresponding changes in electricity demand. For most months, the increase in temperature will likely reduce the need for space heating and electricity demand. Small increases in demand are projected for June and July; however, the arrows indicate that these are considered underestimates by the study's authors. The analysis does not account for increases in the availability of air conditioning, which will likely increase summer demands. Reproduced with permission from NWPCC (2005).[4]

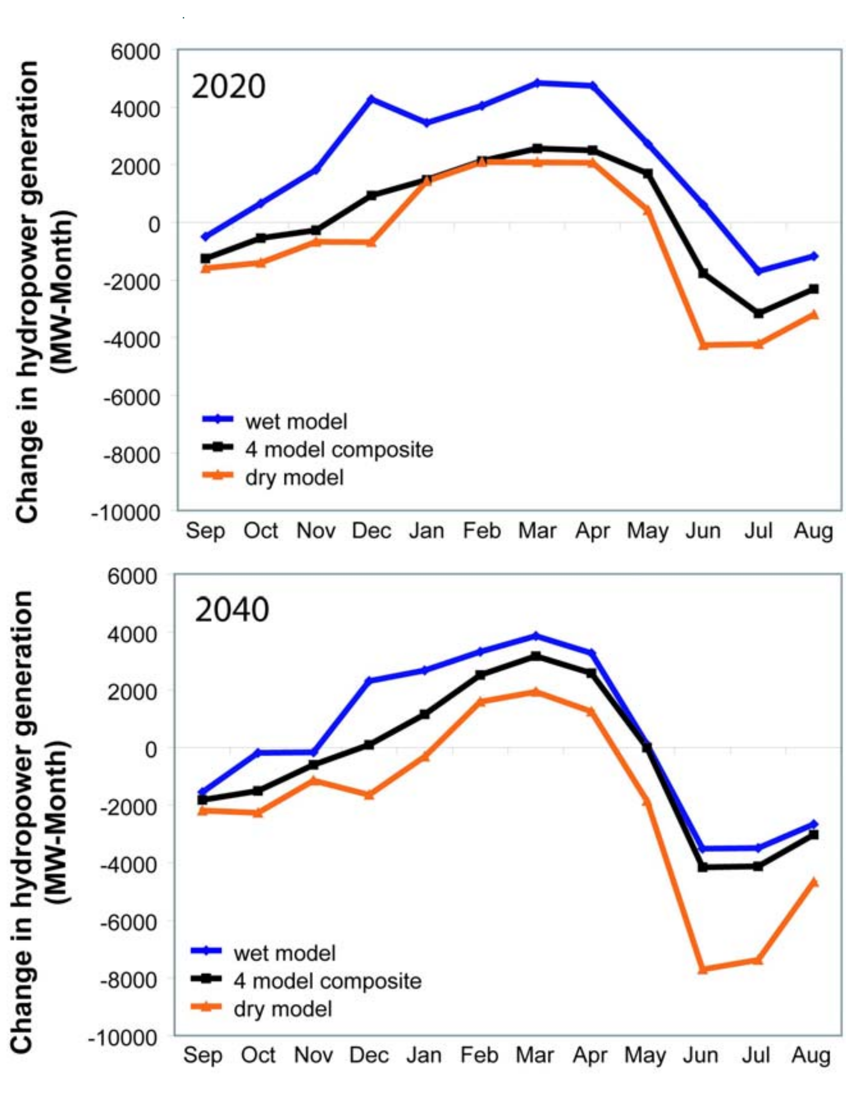


Figure 15. Projected climate impacts on hydroelectricity generation for the 2020s and the 2040s. The graphs show estimated changes in hydropower generation for three sets of climate models. The blue line corresponds to a relatively wet climate model; the orange line represents a relatively dry climate model; the black line represents the average of four climate models (one wet, one dry, one cool, and one warm) and represents a "middle of the road" projection. Increased generation will likely be possible during the winters; while the summers may experience reduced generation. The magnitude of the increases are contingent on the direction of the precipitation change. All models show especially large reductions in generation for the summer by the 2040s. Figure adapted from NWPCC (2005).[5]

the sensitivity of electricity demand to projected temperature change.[6] Studies show that projected temperature increases of 3-5°F (2-3°C) could reduce monthly wintertime electricity demand across the Northwest Power Pool in excess of 1000 MW-Months by 2040, while demand may increase during July and August.[7] These studies forecast that the net annual change will be for decreased electricity demand; however, they assume no increase in the number of customers with access to air conditioning.

By coupling a relatively "wet" and a relatively "dry" global climate model scenario to hydrological and electricity generation models, the Northwest Power and Conservation Council (NWPCC) in partnership with the CIG has simulated how climate change, specifically an increase in winter flows and reduced spring and summer flows, may affect hydroelectric energy supply in the PNW during the next century *(Figure 15)*.[8] The simulations assume the continuance of current hydropower management practices (i.e., rule curve guidance for filling and drafting reservoirs) and current market conditions (i.e., prices, demands of the extra-regional power market).

Climate change will pose a challenge to the current management of the PNW's hydroelectric power network *(Photo: Fish ladder, John Day Dam, U.S. Army Corps of Engineers)*

The NWPCC estimates that hydroelectric generation will likely increase during the winter months because of increased streamflow (a projection that is highly dependent on future changes in precipitation), and decrease during the summer months, because of decreased water availability. These projections indicate that revenues may increase in the short-term, or during particularly wet decades, as the initial winter gains in generation exceed the summer losses. However, by the 2040s, the situation could be reversed and summer losses could overwhelm winter gains.

The projections presented here attempt to isolate the effect that climate may have on electricity demand and hydropower supply. However, they cannot be considered precise forecasts, as this analysis does not account for all the stresses that are placed on the hydropower management system, especially during the summer low flow period. During this time, hydropower management must confront many issues beyond simply fulfilling the electricity needs of consumers in the PNW (see ***Water Resource Management Box***). Pressure to meet in-stream flow targets prescribed by biological opinions associated with the Endangered Species Act, the need to maintain adequate lake levels at recreation areas such as Lake Roosevelt, and growing summer power demand from California and the Southwest all influence the price and availability of hydroelectric energy in Washington.

These factors are also sensitive to climate change in their own right: given projected changes in summer streamflows, maintaining adequate water levels in Lake Roosevelt and in streams inhabited by salmon will likely become more difficult, especially during the summer. Rising summer temperatures may enhance power demands from neighboring states. The ultimate impacts on PNW hydroelectric power production will depend on all of these factors and on how well the region prepares for these changes. **In the 21st century, earlier peak flows, lower summer streamflows, and a lengthened summer low flow period will likely exacerbate competition over water use for hydropower production, in-stream flow protection, and irrigation.**

Water Resource Management

The institutional prioritization that underlies water management in the PNW plays a crucial role in modulating the magnitude of climate change impacts likely to be borne by each sector (hydropower, water supplies, flooding and stormwater management, forests, fish, or agriculture). Recent studies have shown that the *current* operating system of the Columbia River Basin seeks to fulfill hydropower production quotas and the demands of flood control protocol, often at the expense of in-stream flow requirements and other stream objectives such as recreation in man-made lakes *(Figure 16).*[9] As Figure 16 shows, the current system cannot simultaneously meet the needs of each management objective given today's frequency and severity of low flow conditions.

If current operating policies remain unchanged, projected climate change would further lower the reliability of meeting summer in-stream flow, irrigation, and recreation targets. Any change that would improve the system's ability to fulfill one sector's water needs would inherently require trade-offs from other sectors. For the case of meeting current hydropower demands and in-stream flow targets, it would be a zero-sum game – changes in water resources operations to maintain current levels of in-stream flows for fish *could not be achieved* without decreasing hydropower production. It is important to keep this integrated perspective – that **climate impacts in any single area affect and are affected by climate impacts on other sectors and resources** – in mind when assessing potential climate impacts for individual sectors.

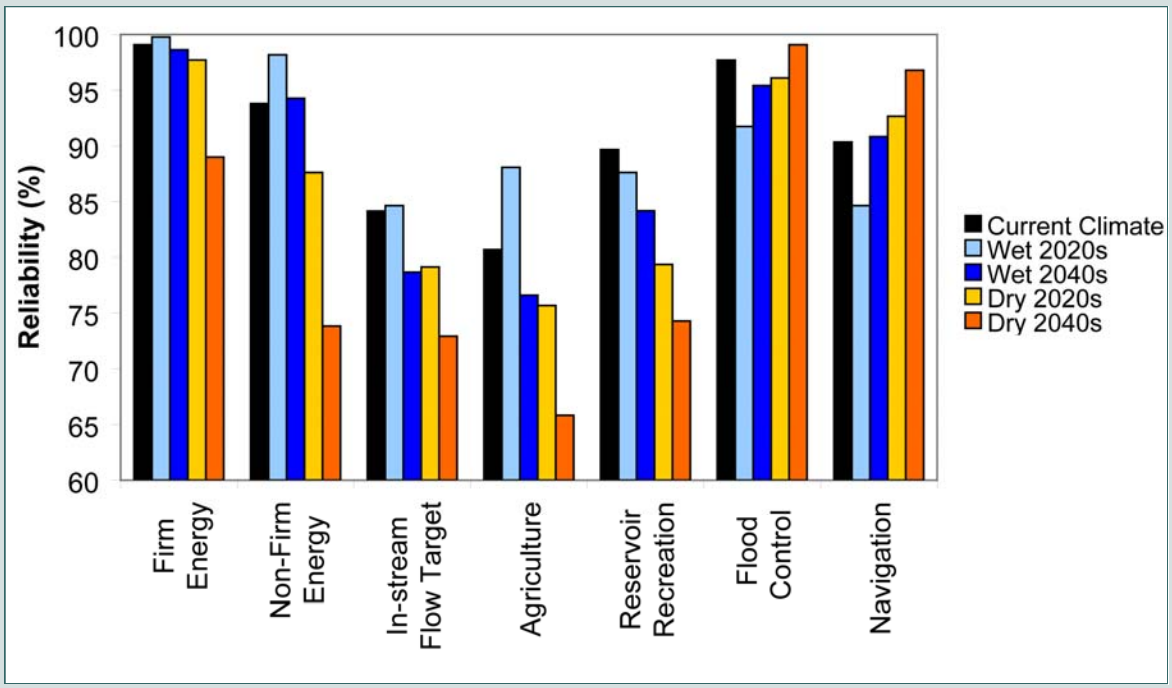


Figure 16. Columbia River basin reliability by sector for current and future climate. The graph shows the reliability of meeting reservoir operation targets estimated using two different climate models for the current climate, the 2020s, and the 2040s. Reliability is calculated as the percentage of years that a system target is met. The dark bars represent the control model run, or current climate. It is clear that targets for in-stream 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).[10]

References and Endnotes

[1] Washington State Department of Community, Trade, and Economic Development. *Washington State Electricity Fuel Mix Report, 2003*. Available for download at http://www.cted.wa.gov/_CTED/documents/ID_1924_Publications.pdf

[2] Sailor, D.J.and J.R. Munoz (1997), Sensitivity of Electricity and Natural Gas Consumption to Climate in the USA – Methodology and Results for Eight States, *Energy*, 22(10): 987-998.

[3] Sailor et al. (1997)

[4] NWPCC (2005)

[5] NWPCC (2005)

[6] Sailor, D.J. (2001), Relating Residential and Commercial Sector Electricity Loads to Climate – Evaluating State Level Sensitivities and Vulnerabilities, *Energy*, 26(7): 645-657; also, (NWPCC) Northwest Power and Conservation Council (2005), *The Fifth Northwest Electric Power and Conservation Plan. Appendix N: Effects of Climate Change on the Hydroelectric System*, May 2005. Available for download at http://www.nwcouncil.org/energy/powerplan/plan/Default.htm

[7] Projections represent an average of projections from the ECHAM4, PCM, HadCM2, and HadCM3 global climate models.

[8] Projections represent an average of projections from the ECHAM4, PCM, HadCM2, and HadCM3 global climate models.

[9] Miles, E.L., A.K. Snover, A.F. Hamlet, B. Callahan, D. Fluharty (2000), "Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water resources of the Columbia River Basin", *Journal of the American Water Resources Association*, 36(2): 399-420; also Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier (2004), Mitigating the Effects of Climate Change on the Water Resources on the Columbia River Basin, *Climatic Change*, 62: 233-256.

[10] Miles et al. (2000) used the HadCM2 and ECHAM4 models.

Impacts on Municipal and Industrial Water Supplies

A reliable supply of water is crucial for the communities, businesses, and industries of Washington. Although these various municipal and industrial (M&I) consumers may use water for different purposes, they are all subject to the seasonal cycle of streamflow.

Climate change, especially through increases in temperature, will likely shift the timing and volume of streamflows during the year *(Figure 9)*. **For the 21st century, more frequent occurrences of low streamflow during the summer could exacerbate competition over water resources, making it more difficult to reliably fulfill present commitments to both in-stream and out-of-stream uses.** Impacts will likely be most severe for watersheds where a large portion of the snowpack resides near the current snow line (a transient watershed, see Figures 8 and 9), as well as for watersheds where the current demands are nearing summer sustainable use limits.

The cycle of streamflow and snowmelt is essential in providing water when it is needed. During the summer, naturally occurring low streamflows, low precipitation, and higher temperatures cause the demand for M&I water to increase, sometimes exceeding what is available in streams and rivers *(Figure 17)*. All major M&I water supplies in Washington rely on storage (whether in the form of surface water reservoirs, snowpack, or groundwater) to supplement the water available from streams. For the water systems that service some of the large population centers in Western Washington (the greater areas of Everett, Seattle, Bellevue, and Tacoma) the amount of reservoir storage is small relative to the annual flow of the rivers. Consequently, dry and/or warm winters that result in low snowpack can significantly decrease water available for M&I use during summer months. Dry and/or warm conditions during the summer also tend to increase water demands. Both changes would extend the summer drawdown period, when water suppliers are relying exclusively on reservoir storage. The droughts of 1987, 1992, and 2001 illustrate the conflicts that can occur between water supply for people and in-stream water needs.

Recent studies on the M&I water supply systems servicing the cities of Seattle, Washington[1] and Portland, Oregon[2] demonstrate the magnitude of potential climate change impacts. By employing a

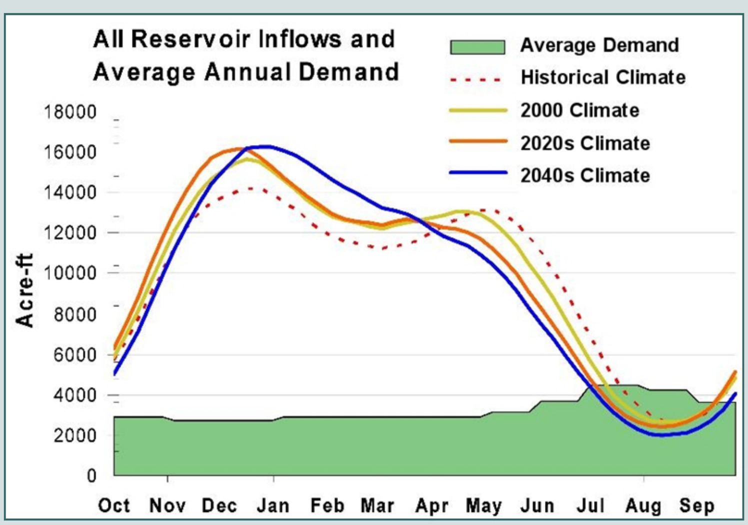


Figure 17. Historical, current, and projected reservoir inflows for Seattle's water supply. The curves show the monthly inflow volumes for different years. The dashed line represents typical conditions during the 20th century. The yellow line represents estimates from four climate models for the year 2000. The orange and blue lines correspond to the same models for the 2020s and 2040s, respectively. The green area corresponds to the average monthly demand observed in Seattle, omitting years where voluntary or mandatory summer consumption curtailments were implemented. Even under current climate and operating conditions, late inflows are less than the demand. Future warming is likely to reduce early summer inflows, thereby increasing the size and lengthening the time of the summer inflow-demand deficit. Reproduced with permission from Wiley (2004).[3]

series of linked models (global climate, hydrology and reservoir management)[4] the studies show that changes in the timing and volume of streamflow due to rising temperatures could significantly reduce summertime reservoir inflow, storage, and yield in the 21st century. For Seattle, the water levels associated with the 50-year low flow would return every 10 years *(Figure 18).* These conditions could have significant consequences for fish. The salmon that rely on the waters of the Cedar River to migrate to the Puget Sound would have their chances of survival diminished by more frequent low flow conditions.

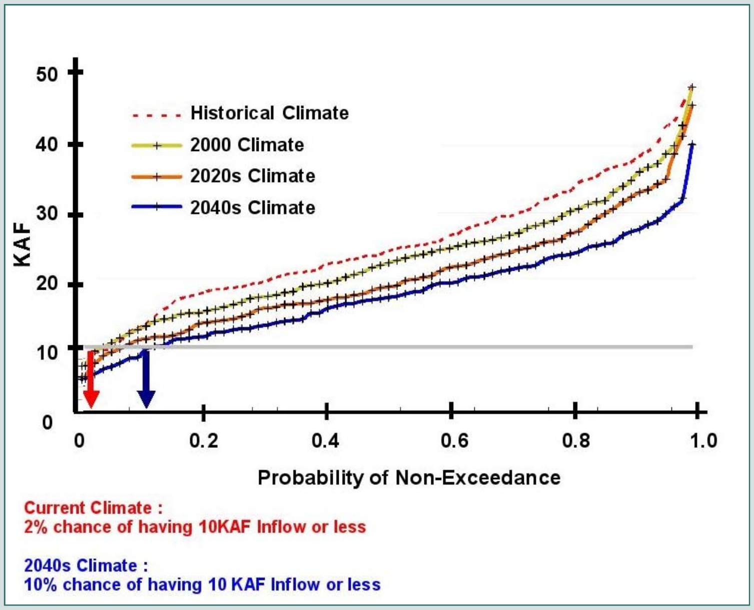


Figure 18. Historical, current, and projected probability of achieving combined June-September reservoir inflow amounts for Seattle's water supply. This graph demonstrates how the chances of receiving a particular volume of summer inflow (in thousand acre-feet (KAF)) are likely to decrease with future warming. As in Figure 17, the dashed curve corresponds to average 20th century conditions; the yellow line corresponds to year 2000 conditions as estimated by four climate models; the orange and blue lines correspond to future model projections for the 2020s and 2040s. The gray line indicates an inflow of 10 KAF. Based on its intersection with the dotted and yellow lines, it indicates that an inflow of 10 KAF has a probability of 0.02, i.e., there is a 2% chance that flows will be at or below 10 KAF under current climate conditions. The projections for the 2020s and 2040s intersect the gray line at a higher level of probability, indicating increased probabilities for the same low flow. For the 2040s, there is a 10% chance that inflows will be at or below 10 KAF. Reproduced with permission from Wiley (2004).[5]

Similar challenges have been identified for Portland. By the 2040s, Portland's annual minimum storage could be reduced by 1 billion gallons (~ 10% of current storage) in 50% of the years. For Portland, climate change could account for half the changes in supply and demand attributed to regional growth alone *(Figure 19)*, making climate information an important factor in M&I water resource planning. In other words, planning only to meet the increased demands caused by future growth would cause Portland planners to underestimate their future supply needs by approximately 30%.

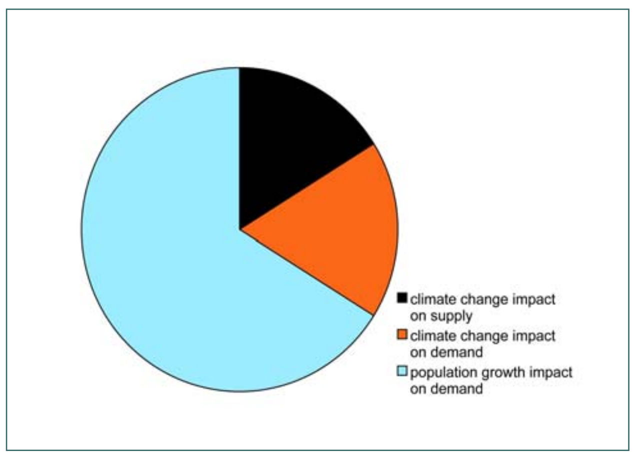


Figure 19. Factors controlling Portland's (Oregon) projected future water supply The pie chart is derived from projections of Portland's Bull Run watershed for the 2040s. The study found that while population growth has the largest impact on future water supply needs, the additional impact of climate change on supply and demand by 2040 is considerable. Climate change would increase supply needs by 50% of the amount required to meet population growth alone. Based on results from Palmer and Hahn (2002).[6]

References and Endnotes

[1] Wiley, M.W. (2004), *Analysis Techniques to Incorporate Climate Change Information into Seattle's Long Range Water Supply Planning,* Master's Thesis, University of Washington, Department of Civil and Environmental Engineering, 201pp.

[2] Palmer, R.N., and M. A. Hahn (2002), *The Impacts of Climate Change on Portland's Water Supply: An*

Investigation of Potential Hydrologic and Management Impacts on the Bull Run System. Report prepared for the Portland Water Bureau, University of Washington, Seattle, 139pp.

[3] Wiley (2004)

[4] Wiley (2004) employed projections from the ECHAM4, GFDL, HadCM3, and PCM global climate models.

[5] Wiley (2004)

[6] Palmer and Hahn (2002) employed projections from the ECHAM4, PCM, HadCM2, and HadCM3 global climate models.

Impacts on Flood and Stormwater Management

The frequency and severity of flooding events in natural river basins are sensitive to changes in both temperature and precipitation, in ways that differ for different river basin types.

In transient watersheds, increases in temperature can cause more precipitation to fall as rain instead of snow, leading to an increase in flooding in winter even if precipitation remains the same.[1] Historically, cool seasons (October-March) experiencing greater precipitation have exhibited a greater likelihood of flooding along rivers overall. If winter precipitation increases in the future, as some models suggest, the risk of flooding would be compounded. **In snowmelt dominant basins, several competing factors are present. Reduced snowpack may tend to reduce flood risks in the spring, however elevated soil moisture in April (due to earlier snowmelt) may also tend to increase vulnerability to flooding caused by spring storms.**

In the urban setting, flooding poses challenges to stormwater management. Here, changes in temperature and average seasonal precipitation volumes play less of a role in determining the frequency and severity of flooding events. The leading climate influence is the frequency and intensity[2] of individual cool season storms. **It is unclear how urban stormwater flooding may change in the future, as modeling the behavior of individual storms, and their potential response to global warming, is beyond the capabilities of global climate models at this time.**[3]

Researchers at the University of Washington are attempting to employ higher resolution (smaller spatial scale) models to examine how the frequency and intensity of storms in the PNW could change as a consequence of global warming. In the future, their results could be combined with existing models of the land surface and the local and regional hydrologic system to provide projections of stormwater flooding events in cities and communities.

Hamilton, Skagit County, Washington, October 2003 Flood, www.skagitriverhistory.com

Endnotes

[1] The increase will likely be an increase in moderate floods. The largest floods in the historical record tend to occur when temperatures are already above freezing (colloquially, the conditions are known as "the Pineapple Express").

[2] Measured by the rain rate and the total amount of rain delivered from storms.

[3] Some global climate models indicate an increase in the frequency of intense storms in areas where precipitation is projected to increase. However, such projections are less certain than temperature or average precipitation projections, and they are only valid as a global or sub-continental average. Many local factors, such as topography, play an important role in determining storm frequency and intensity. These factors are often not well resolved by global climate models. As a result, changes in storm frequency and intensity are likely to be different at smaller spatial scales (e.g. for the Puget Sound).

Impacts on Forests

The diversity of PNW forests reflects the wide range in climatic regimes across the region. Heavy precipitation in the lowlands along the Pacific Coast supports temperate rain forests. The West side of the Cascades is populated by red alder and Sitka spruce at lower elevation, giving way to Pacific silver fir and mountain hemlock at higher elevations. The East side of the Cascade crest is much drier and ponderosa pine is prevalent.

This distribution of species has not been constant over time. The forests we observe today have been continuously evolving in response to climate fluctuations at many timescales. On long time scales (centuries, millennia), variations in temperature and precipitation patterns have directly influenced tree growth and regeneration, as well as forest community structure. On shorter timescales, climate can influence the establishment and growth of individual trees, while indirectly affecting forests through disturbances such as fire and pest outbreaks. Both the direct and indirect impacts of climate interact to shape where and when certain tree species thrive, and which species can coexist in the same habitat.

During the 21st century and those following, climate change will likely reorganize PNW forests. **Some tree species will likely shift their geographic range, often migrating to higher elevations and latitudes. Other species may be unable to adapt to changing climate conditions and their numbers could decline**. However, these direct impacts will likely occur very slowly, spread out over many human generations, and may be difficult to observe. On shorter timescales, more noticeable changes with potentially significant socioeconomic implications will likely result from climate change's influence on the frequency, severity, and duration of disturbances. Specifically, **rising temperatures could create favorable conditions for fire and pest outbreaks. If realized, severe fire and pest outbreaks could reduce the diversity and extent of PNW forests over the coming decades.**

Direct impacts of climate change on forests will depend on how climate affects the factors limiting a tree species' growth and regeneration in a particular location. For example, at higher elevations where the presence of snowpack and short growing seasons limit the range of subalpine fir,[1] projected temperature increases could allow the firs to grow at higher elevations. Warmer temperatures would lengthen the growing season for mature trees and enhance seedling establishment by reducing snow pack. However, for subalpine firs in lower elevation forests, forest extent and productivity are limited by summer soil moisture. Increased temperature and earlier snowmelt would likely enhance summer drought stress, especially if summer precipitation is also reduced. Productivity and regeneration of subalpine firs at lower elevations would likely decline as the species faces more frequent and longer lasting droughts.

Carbon dioxide fertilization is another pathway by which climate change could directly affect PNW forests. Increased atmospheric concentrations of CO_2 tend to increase the photosynthetic rate and water efficiency of plants and trees, increasing their productivity. However, field studies find that forests often display a minimal growth response to increased levels of CO_2. It has been suggested that if such a fertilization mechanism exists, it may only be transient, yielding benefit for a short period of time until trees adjust to the elevated CO_2, or until the stress caused by higher temperatures overwhelms the positive effect of CO_2 fertilization. Fertilization remains uncertain, and active research is directed toward resolving the impact it may have on PNW forests.

Indirect climate impacts will likely be detrimental to forests. With increasing temperatures and potential reductions in soil moisture, trees could become increasingly heat- and moisture-stressed, making them more susceptible to fire. Fires could be more frequent, cover larger areas, and expand to areas with historically low fire risk. A recent climate modeling study for the West shows that the average annual area burned in Washington could increase by a factor of two to five by the end of the 21st century.[2] This result is based on a relatively cool climate model[3] that projects little precipitation change, making the fire risk increase a conservative estimate.[4] It also demonstrates that temperature increases may be more important than precipitation changes in increasing fire frequency and size.

Pests may become more prevalent, as higher temperatures enhance reproduction rates. Milder winters could increase survival rates for insect larva and adult reproductive rates may increase, allowing pests to increase their abundance and migrate northward or up in elevation. Pests could also capitalize on heat- or moisture-stressed forests, as these trees are more susceptible to infestation. Looking at the past decade, we see a potential harbinger of climate change impacts as the observed warming trend has been correlated with more frequent and severe outbreaks of bark beetles in the forests of the PNW and British Columbia (*Figure 20*).

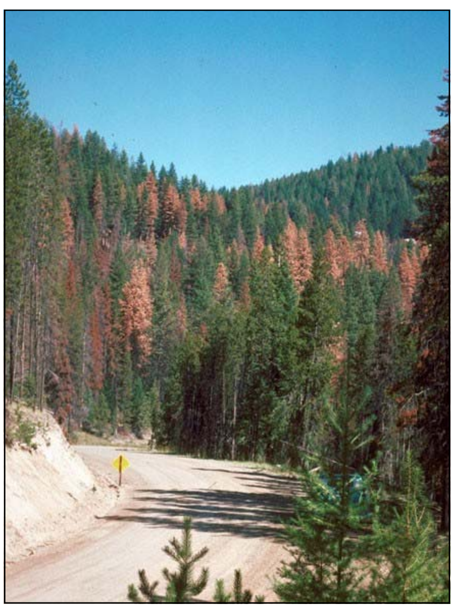


Figure 20. Evidence of beetle destruction near Granite Creek, Washington. The photo shows red trees, infested and killed by the Mountain Pine Beetle, intermingled with healthy trees. Beetles are one type of pest that may expand its range and abundance in a warmer climate. Photo taken by Dave Powell, USDA Forest Service.[5]

The interactions among fire and pest outbreaks are often two-way: fire and pest disturbances can enhance one another. The presence of dead or weakened trees that have suffered pest infestation generally increases fire risk; areas that have experienced fires can provide ideal hatching grounds for insects.

References and Endnotes

[1] Peterson, D. W., D. L. Peterson, and G. J. Ettl. (2002), Growth responses of subalpine fir *(Abies lasiocarpa)* to climatic variability in the Pacific Northwest, *Canadian Journal of Forest Research*, 32(9): 1503-1517.

[2] McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote (2003), Climatic Change, Wildfire, and Conservation, *Conservation Biology*, 18(4): 890-902.

[3] McKenzie et al. (2003) uses projections from the PCM global climate model.

[4] The study uses the PCM model, which is relatively insensitive to greenhouse gas forcing and consistently projects smaller temperature increases than other models. It also employs the B2 emissions scenario, which assumes a smaller global population and a more environmentally sustainable economy, and consequently, a lower greenhouse gas concentration than the scenarios quoted in the other studies in this booklet. The projections are for 2070-2100.

[5] Photo available online at http://www.forestryimages.org/browse/detail.cfm?imgnum=1207054

Impacts on Fish

Climate has a powerful influence on fish populations because it is a major factor determining the structure and functioning of riparian, lake, estuarine, and ocean ecosystems. Recent events have demonstrated the consequence of climate for PNW fish. During the drought of 2001, hundreds of thousands of juvenile salmon were stranded by low flow in the Columbia River and were unable to travel to the Pacific Ocean. Above average ocean temperatures and reduced coastal ocean upwelling in spring 2005 resulted in juvenile marine salmon populations that were 20 to 30 percent below average along the PNW coast.[1] A 50-year warming trend in Lake Washington's water temperatures has increased the frequency and duration of summer stratification, whereby warm surface waters are unable to mix with cooler, nutrient-rich bottom waters, reducing the available food for fish and inducing algal blooms.[2] High stream temperatures in 2004 have been implicated in major sockeye salmon die-offs in the Fraser River.[3]

Climate change could place additional stresses on fish populations in the PNW. **Projected temperature increases and streamflow changes could create environmental conditions that are inhospitable to many PNW cold water fish populations (e.g., salmon, trout), potentially outpacing their ability to adapt.** Higher stream, lake, and ocean temperatures may exceed the tolerable limits for many fish. Increases in lake or ocean stratification

Pacific Northwest Salmon

Salmon play a special role in the economic and cultural identity of the Northwest. Native American populations and early European-American settlers relied on salmon as a food staple. In modern times, salmon remain spiritually, culturally, and economically important to tribal communities. In addition, today’s salmon runs support non-tribal sport and commercial fishing industries. However, as a result of habitat destruction, altered streamflows from dams, overfishing, and competition from hatchery salmon, many wild stocks of salmon have been depleted, and in some cases have gone extinct. As of 1999, there are eight groups[4] of Northwest salmon listed as threatened and one as endangered under the Endangered Species Act, including the Puget Sound chinook.

Salmon's unusual lifecycle *(Figure 21)* make them sensitive to climate changes in a range of aquatic habitats. Salmon spawn and lay their eggs in freshwater. Juveniles spend up to a year in streams before traveling toward brackish estuaries and the ocean, to spend most of their adult life. Salmon then return to their natal streams to reproduce and complete the cycle.

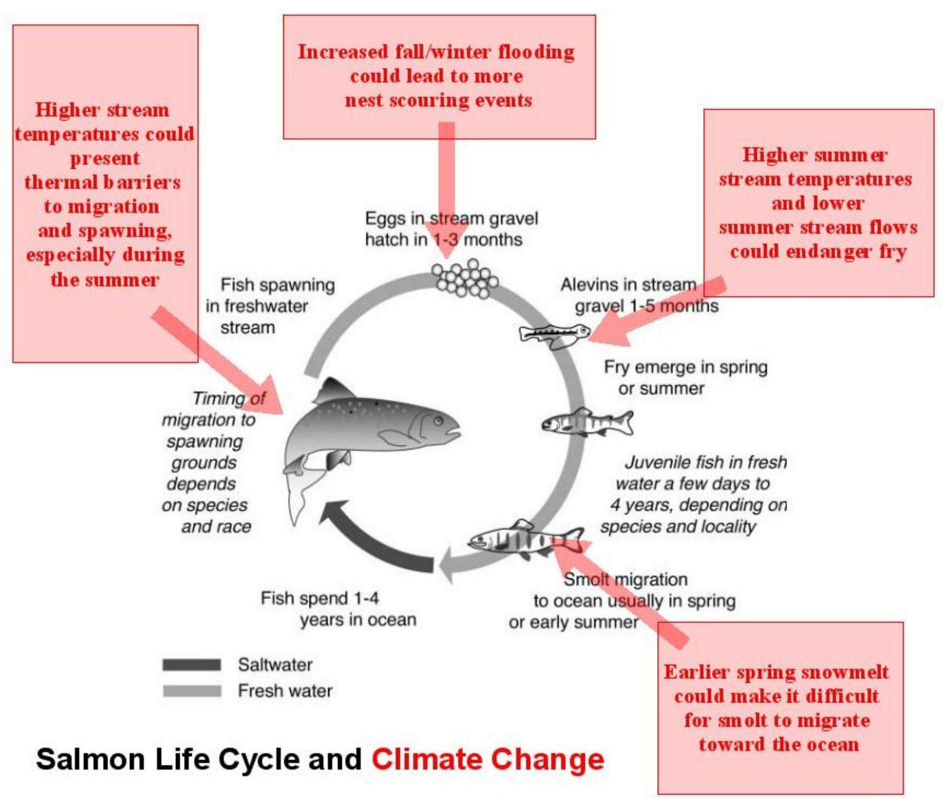
Projected climate change could threaten already imperiled PNW salmon populations. Low summer flows and high stream temperatures can hinder juvenile salmon rearing in streams and adult salmon migrating to their spawning areas. High summer stream temperatures *(Figure 22)* could also present thermal barriers to upstream migration of adult salmon, preventing successful reproduction. While higher winter temperatures may benefit salmon populations in many streams by increasing their metabolic rate and/or stream productivity, reduced winter snow pack and increased winter precipitation will move peak streamflows earlier in the year, potentially increasing the frequency of redd-scouring flood events and robbing spring-migrating juvenile salmon of their “transportation” to salt water. In the ocean, higher temperatures or altered ocean currents affect the availability of food and change the prevalence of predators. However, the effects of human-induced climate change on ocean temperatures and ocean currents are not well understood. Ocean conditions are strongly influenced by surface winds and how these winds might change is not currently known.

could reduce nutrient availability, reducing fish populations and increasing competition in these ecosystems. Areas that currently trend towards to low amounts of dissolved oxygen in deep waters, such as parts of Puget Sound, may see dissolved oxygen levels decrease further, further stressing or even killing fish. Stream-dwelling fish could face an increased frequency of high flows and floods during the winter, an earlier onset of the spring freshet, and more frequent and prolonged high temperature-low flow periods during the summer. All of these changes may interfere with cold water fish habitat and survival rates.

Climate change will likely affect ecosystems by many different pathways – via changes in the environment, such as those described above, and also via changes in other sectors. The impacts of climate change on Washington forests, for example, or the ways in which water resources managers respond to low summer streamflow conditions resulting from climate change, could have important consequences for stream habitat.

Climate change impacts on forests and streams could have important consequences for stream habitat. *Photo: Climate Impacts Group*

Figure 21. Salmon life cycle and climate change. Salmon have a unique life cycle that exposes them to the effects of climate change across many seasons and habitats. The red boxes explain how projected temperature and hydrologic changes may impact salmon during various phases of their life cycle.



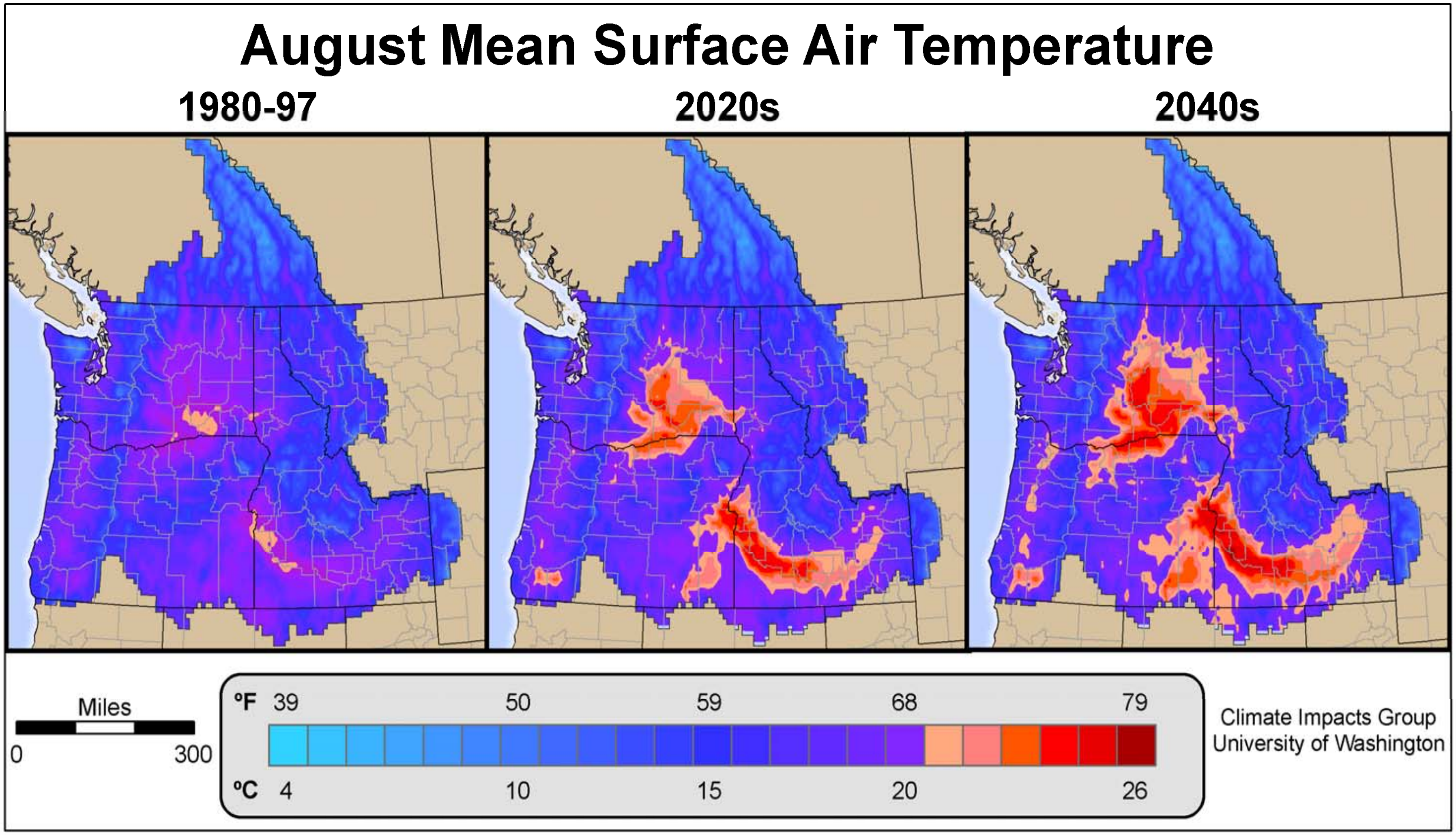


Figure 22. Recent and projected average August surface air temperature in the Columbia Basin. The left panel shows observed August surface air temperatures in the Columbia River Basin. Areas where the average air temperature is greater than ~70°F (21°C), which generally leads to high unsuitable for salmonids (shown in red). Future temperature projections made with a relatively cool climate model (PCM) are shown in the center and right panels. Future warming may threaten salmon by increasing stream temperatures across a wide range of their current habitat.

References and Endnotes

[1] Stanton, C. (2005), "Warmer Oceans May Be Killing West Coast Marine Life", *Seattle Times*, July 13, 2005. Available online at http://seattletimes.nwsource.com/html/localnews/2002377292_ocean13m.html

[2] Winder, M., and D. E. Schindler (2004), Climatic effects on the phenology of lake processes, *Global Change Biology* 10: 1844-1856; also, Stiffler, L. (2005), "Lake Washington's ecosystem in trouble", Seattle Post-Intelligencer, July 11, 2005. Available online at http://seattlepi.nwsource.com/local/232047_lakewash11.html

[3] Fisheries and Oceans Canada (2005), *Effects of High Water Temperature on Fraser River Sockeye in 2004*, 2004 Southern Salmon Fishery Post-Season Review. On-line report, accessed October 3, 2005. Available online at http://www-comm.pac.dfo-mpo.gc.ca/publications/2004psr/Williams5_e.htm

[4] Although there are only seven species of salmon, many distinct subgroups (evolutionarily significant units or ESUs) have isolated themselves based on their behaviors and habitats. Under the Endangered Species Act, individual ESUs can be listed as threatened or endangered. Mantua, N.J., R.C. Francis, D. Fluharty, and P.W. Mote (2005), Climate and the Pacific Northwest Salmon Crisis: A Case of Discordant Harmony, Chapter 7 in *Rhythms of Change: Climate Change Impacts on the Pacific Northwest*, Cambridge, Massachusetts: MIT Press. (in review)

Impacts on Agriculture

Agriculture is an integral part of the Washington economy and important to the vitality of many communities across the state. Agricultural commodities produced in Washington have an annual value of over $5 billion[1] and the food industry employs over 160,000 people.[2] Apples, milk, wheat, potatoes, and cattle represent Washington's top five agricultural products by production value, with apples usually worth more than $1 billion per year. Nationally, Washington leads the U.S. in production of apples, cherries, hops, and mint.

Projected increases in temperature and atmospheric CO_2 concentrations will likely increase crop yields in places where sufficient soil moisture or irrigation water is available. Some crops could benefit from a longer growing season but would require more water due to a longer irrigation season. In areas without irrigation, or in areas where soil moisture is projected to decrease, crops could suffer more days of heat and moisture stress. **Shifts in the timing of peak streamflow could reduce the availability of irrigation water during the summer when it is needed the most. Projected increases in temperature may benefit pests and weeds, mitigating projected yield and productivity increases.** Overall, the impacts will vary throughout the region, highly contingent on the types of crops being produced and the availability of water. The consequences of climate change for the agricultural sector will also depend strongly on the nature of adaptive measures adopted locally as well as on how climate change affects agricultural production elsewhere in the world.

Temperature, precipitation, and atmospheric CO_2 concentrations all influence plant development. Increased temperature can directly improve crop growth, as long as a particular plant's heat tolerance is not exceeded and sufficient moisture is available. Generally, increased precipitation aids crops, as long

Photo: Climate Impacts Group

as water-logging (or storm damage) does not occur. Under conditions where sufficient nutrients and water are present, increased CO_2 levels will theoretically benefit most plants, increasing water efficiency and photosynthetic rate. However, it has also been suggested that the CO_2 fertilization effect may lead to nutrient-poor crops[3] or that increases in plant productivity may vanish over time as other nutrients become limiting.[4] Alternatively, CO_2 fertilization may enhance weed growth, which could compete with crops for water and nutrients or require increased herbicide use.

Climate change studies have identified potential futures for Washington agriculture. Modeling efforts by researchers at the Pacific Northwest National Laboratory (PNNL) demonstrate that dryland and irrigated winter wheat production in Eastern Washington could be enhanced by projected climate change.[5] Their results, which assume a warmer and wetter climate for the region, show that winter wheat would benefit from CO_2 fertilization and experience fewer incidences of cold and moisture stress. The area for winter wheat production could expand, especially to higher elevations. Similar studies for alfalfa hay also show some production benefits; however, the increases are smaller and contingent upon the positive effect of CO_2 fertilization.[6]

Projected climate change will likely pose serious challenges to farmers and ranchers relying on irrigation. The shift in timing of peak streamflow earlier in the year may lead to shortages during the summer, when demand is at its highest. Assuming that water demand for in-stream flow uses also peaks during the summer, increased competition for water is likely.[7] In locations where irrigation districts or individual agricultural operations have junior water rights, prorationing of summer water may become more frequent *(Figure 23)*. The inability of the irrigation system to reliably provide water during the summer could severely inhibit production of high-value perennial crops, where one summer without water could stifle plants for five or ten years to come.

Although specific studies have not been performed in the PNW, projected climate change could increase the threat of agricultural pests and diseases. Warmer temperatures could increase the number of insect life cycles per year and expand the range of some pests. Projected climate change could alter the rates of development of pathogens and modify crop resistance to diseases.[8] By statistically relating the use of pesticides to previous climates, a recent assessment indicates that climate change may increase the need

Yakima River Basin Agriculture

Agriculture in the Yakima River Basin produces crops with annual market values of ~ $1 billion, mostly from perennial crops such as apples and grapes. Approximately half of the users on the Yakima have junior water rights, including many of the perennial crop growers. In the low water year of 1994, many junior water rights holders faced prorationing of their water rights, resulting in economic losses on the order of $140 million.[9]

Climate change in the Yakima, a snowmelt driven basin, would likely cause peak streamflows to arrive earlier in the year, reducing summer streamflow. As peak flows occur earlier in the year, less water may be available late in the summer, when irrigation demands are high. According to a recent study, the amount of water available for irrigation in the Yakima Valley would fall an average of 20 to 40 percent in a typical year by 2050, due to rising temperatures *(Figure 23)*.[10] Another study shows that an increase of 3.6°F (2°C) could raise the probability of severe water prorationing for junior rights holders over 50%, an increase by a factor of four.[11] This increase in temperature and water scarcity would translate into financial losses of nearly $100 million per year in the coming decades.

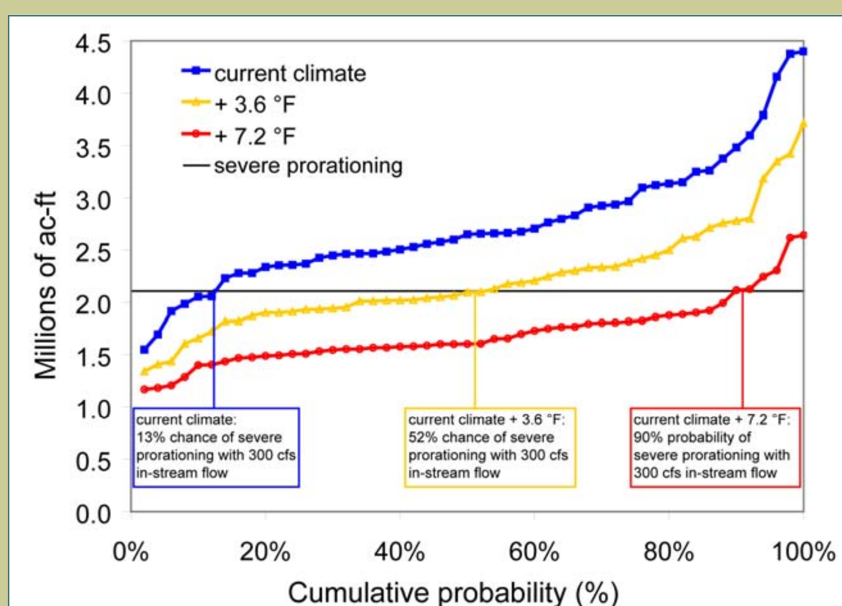


Figure 23. Current and projected probability of prorationing irrigation water for junior rights holders in the Yakima River Valley. In the current climate, severe prorationing (junior water rights holders receiving 50% or less of their allotment) occurs in the Yakima Valley when available water supply falls below ~2 million acre-feet of water (denoted by the yellow line). Currently, this happens ~14% of the summer. Warmer climates will likely increase the frequency of severe prorationing dramatically. A 3.6°F (2°C) warming, which could occur around the 2020s, is projected to increase the frequency of severe prorationing to over half of the years; 7.2°F (4°C) of warming, which could occur by 2100, could make severe prorationing happen in over 90% of the years. Reproduced with permission from Scott et al. (2004).[12]

for pesticides.[13] The impact of pests and diseases on agriculture represents an important area of concern; however, more research is needed to improve our understanding of the interactions of among pests, diseases, crops and climate.

References and Endnotes

[1] (USDA) U.S. Department of Agriculture, Washington Agricultural Statistics Service, *Agriculture in Washington, Washington 2004 Annual Bulletin.* Available for download at http://www.nass.usda.gov/wa/annual04/content4.htm

[2] Washington State Department of Agriculture website: http://agr.wa.gov/CropMap.htm

[3] Thomson, A.M., N.J. Rosenberg, R.C. Izaurralde, and R.A. Brown (2005), Climate Change Impacts for the Conterminous USA: An Integrated Assessment, Part 5, Irrigated Agriculture and National Grain Crop Production, *Climatic Change,* 69: 89-105; also, Ramirez, J. and B. Finnerty (1996), CO_2 and Temperature Effects on Evapotranspiration and Irrigated Agriculture, *Journal of Irrigation and Drainage Engineering,* 122(3): 155-163.

[4] Thomson, A.M., R.A. Brown, N.J. Rosenberg, R. C. Izaurralde, and V. Benson (2005), Climate Change Impacts for the Conterminous USA: An Integrated Assessment, Part 3, Dryland Production of Grain and Forage Crops, *Climatic Change,* 69: 43-65; also, Gitay, H., S. Brown, W. Easterling, and B. Jallow (2001), Ecosystems and Their Goods and Services, pp.235-342 in McCarthy et al. (eds.), *Climate Change 2001: Impacts Adaptation and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).* Cambridge University Press, Cambridge.

[5] Thomson, A.M., R.A. Brown, S.J. Ghan, R.C. Izaurralde, N.J. Rosenberg, and L.R. Leung (2002), Elevation Dependence of Winter Wheat Production in Eastern Washington State with Climate Change: A Methodological Study, *Climatic Change*, 54: 141-164.

[6] Thomson et al.(2005), "Climate Change Impacts for the Conterminous USA: An Integrated Assessment, Part 3. Dryland Production of Grain and Forage Crops"

[7] Miles, E.L., A.K. Snover, A.F. Hamlet, B. Callahan, D. Fluharty (2000), "Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water resources of the Columbia River Basin", *Journal of the American Water Resources Association*, 36(2): 399-420.

[8] Coakley, S., Sherm, H. and S. Chakraborty (1999), Climate Change and Plant Disease Management, *Annual Review of Phytopathology*, 37:399-426.

[9] Parson, E.A., P.W. Mote, A. Hamlet, N. Mantua, A. Snover, W. Keeton, E. Miles, D. Canning, and K.R. Ideker (2001), *Potential Consequences of Climate Variability and Change for the Pacific Northwest,* Chapter 9 in *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. Foundation Report,* National Assessment Synthesis Team, U.S. Global Change Research Program.

[10] Details of the analysis of water availability in the Yakima River Basin can be found in Scott, M.J., L.W. Vail, C.O. Stöckle, and A. Kemanian (2004), Climate Change and Adaptation in Irrigated Agriculture - A Case Study of the Yakima River, In *Proceedings of the UCOWR/NIWR Annual Conference, July 20-22, 2004, Portland, Oregon,* PNWD-SA-6448. Pacific Northwest National Laboratory, Richland, WA; also in Scott, M. J., L.W. Vail, C. Stöckle, A. Kemanian, K.M. Branch, R. Prasad, M.A. Wigmosta, J.A. Jaksch (2005), "Adapting Irrigated Agriculture to Climate Variability and Change", PNWD-SA-6743, presented at the 2005 AAAS Annual Meeting, American Association for the Advancement of Science, February 20, 2005, Washington D.C.

[11] Scott et al. (2004)

[12] Scott et al. (2004)

[13] (USGCRP) U.S. Global Change Research Program (2000), *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change,* National Assessment Overview, Agriculture Sector Summary, National Assessment Synthesis Team. Available for download at http://www.usgcrp.gov/usgcrp/Library/nationalassessment/15AG.pdf

Changes Beyond the 2040s

Given the long time that many greenhouse gases persist in the atmosphere[1] and the difficulty of changing global fuel consumption patterns, the earth is essentially committed to continued warming for the coming several decades.

Current projections call for the earth's climate to continue to change, with temperatures continuing to rise, throughout the second half of the century and beyond. Current projections are for global average temperature to increase 2.5 to 10°F (1.4-5.8°C) by 2100. The uncertainty in this estimate (that is, the large range in possible future temperature) is partially a result of disagreement among different climate models about how climate will actually change when atmospheric greenhouse gas concentrations increase. About half of the uncertainty, however, results from the impossibility of projecting what those future greenhouse gas concentrations will be.

Because climate change impacts occurring during the latter half of the 21st century are contingent on emissions that have yet to occur; socioeconomic and political choices become increasingly important for determining how much climate change will occur as we look further forward in time. All kinds of choices, made both by individuals and by society as a whole, matter for future emissions. The rate of population growth, the type and amount of energy use, the development and spread of technology, and the rate and reach of globalization will all affect the rate at which greenhouse gases are emitted in the future. Will concentrations of atmospheric CO_2 rise from today's level of 375 parts per million by volume (ppmv) to 540 ppmv, 970 ppmv, or something higher by 2100? Will the earth warm another 2.5°F by 2100? Or by 10°F? Or even more?

When looking far into the future (past 2050), the warming and impact projections are based on assumptions regarding future global socioeconomic and political choices. Accordingly, these projections should be judged less certain than projections for the near future.

Using a variety of emission scenarios for the future, global climate models project possible PNW temperature increases for the 2080s to fall between 2.9 to 8.8°F (1.6 to 4.9°C). It is important to note that the range in temperature increases for the late 21st century does not reflect the full range of possibilities – simply the range of the scenarios, which represent a finite number of future socioeconomic and political paths. The actual change could be higher or lower. The range of the scenarios, as well as the divergence in climate models late in the century, is shown by the wide spread in projected temperature increases on the right side of Figure 4.

Despite the uncertainty of long-term projections of climate conditions, all scenarios call for a warmer future. For impacts that are strongly temperature dependent, the severity of pre-2050 impacts could be augmented by additional temperature change. Warming in the second half of the 21st century could:

- Exacerbate declines in snowpack and shift the timing of peak streamflow for snowmelt dominant and transient watersheds even earlier in the year. Some transient watersheds may no longer be fed by snow and could become rain dominant.

- Increase stream and lake temperatures, posing further challenges to the ecosystems that reside in freshwater *(Figure 11)*.

- Make it even more difficult to simultaneously generate hydroelectric power and reliably fulfill in-stream flow targets, lake levels sufficient for recreation, and water supplied for irrigation *(Figure 16, Figure 23)*.

- Increase winter electricity generation and lower demands. Summer electricity demand could continue to increase while generation could decline, leading to shortfalls.

- Lower summer M&I water supplies. Demands could continue to increase, as a result of both population growth and climate change.

- Increase forest fire and pest outbreak frequency and severity. Forest communities may have different compositions than today, with many species migrating poleward and upward in elevation.

- Increase the frequency of die-off events for cold water fish, such as salmon, if they are unable to adapt their behavior to the new climate conditions. Increased temperatures and stratification could disrupt ecosystems in Lake Washington or the Puget Sound.

- Increase stress on farmers and ranchers who rely on summer irrigation water supplies. While some crops may benefit from increases in temperature and CO_2 where sufficient water is available, pest and pathogen outbreaks could become more frequent or severe.

As mentioned above, the uncertainty inherent to projecting impacts far into the future makes any precise statements regarding impacts very difficult, but it is important to note that the cause of impacts in Washington may not be related solely to regional climatic changes. Changes in the global oceans such as sea level rise, and the loss of ice in the Arctic Ocean may significantly affect the viability of global shipping routes and could affect Washington's commerce, for example. Likewise changes in global supplies and markets for food could affect the viability of Washington's agricultural economies. Impacts to human health, although currently very uncertain, may prove to be a global issue rather than a regional one. These issues present fundamental challenges to current planning frameworks — challenges that deserve serious attention.

Endnotes

[1] On average, a carbon dioxide molecule remains in the atmosphere for a century; many greenhouse gases have atmospheric lifetimes lasting thousands of years (Table 1).

Climate Impacts Group
Center for Science in the Earth System
University of Washington
www.cses.washington.edu/cig