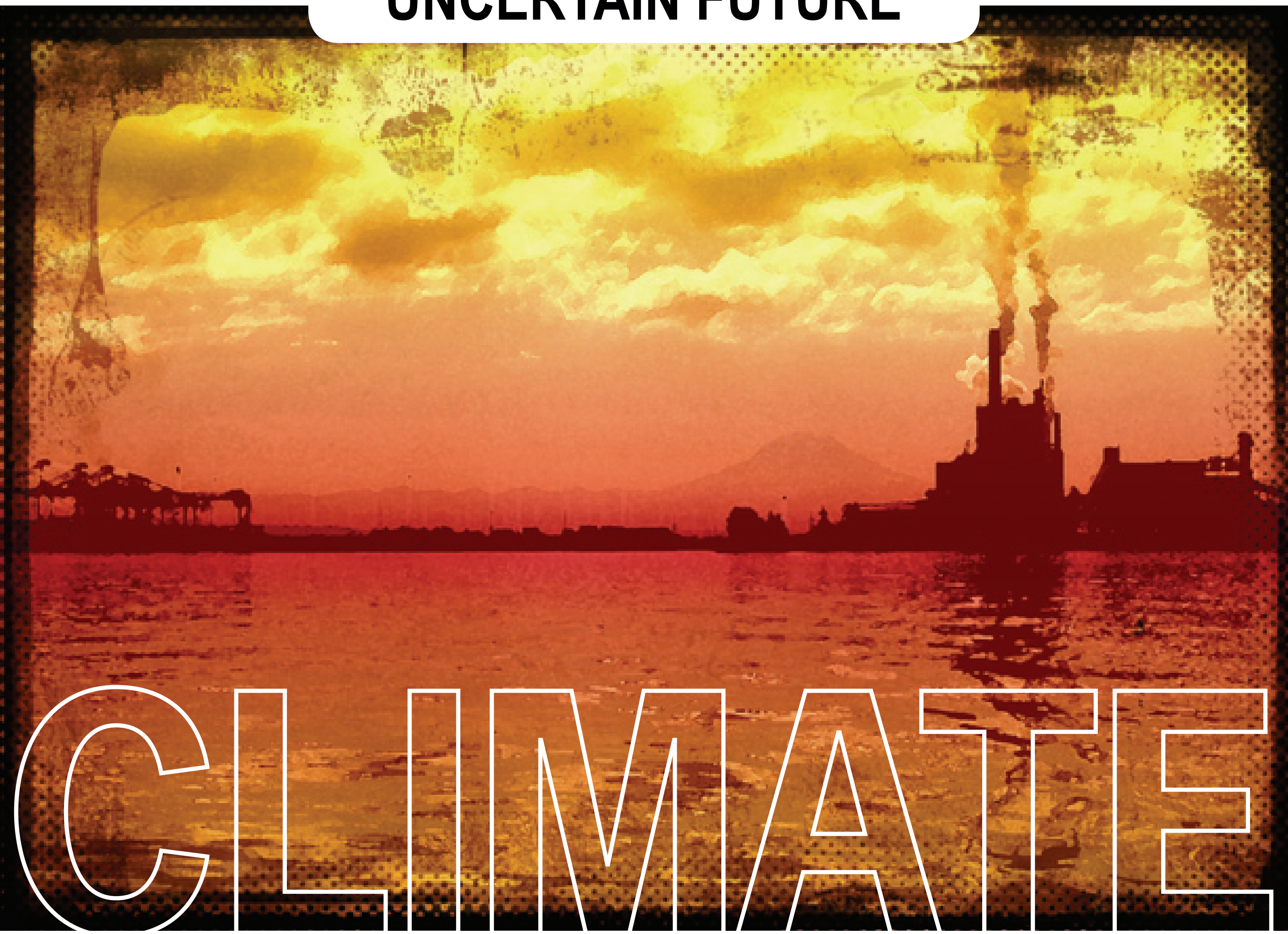
UNCERTAIN FUTURE



CLIMATE CHANGE AND ITS EFFECTS ON PUGET SOUND

The Climate Impacts Group, University of Washington
commissioned by

PUGET SOUND ACTION TEAM
Office of the Governor | State of Washington

October 2005

It takes the ocean centuries to fully communicate with the atmosphere. Even if we stopped emitting CO_2 today, warming would continue for decades.

Table of Contents

Foreword 4
Executive Summary 6
Introduction 10
Changes in Climate 12
- Global climate change 12
- 20th century climate change in Puget Sound 13
- 21st century climate change in Puget Sound 14

Changes in Snowpack and Stream Flow 16
- Snowpack and stream flow in the 20th century 16
- Snowpack and stream flow in the 21st century 18
  - Flooding 18
  - Glaciers in retreat 18

Changes in the Waters of Puget Sound 20
- Sea level rise 20
- Circulation in Puget Sound 21
- Coastal upwelling 22
- Water quality 22
  - Water temperature 22
  - Salinity 23
  - Stratification 23
  - Dissolved oxygen 24
  - Nutrients 24
  - Fecal coliform and other pollutants 25

Consequences for Marine Ecosystem Structure and Function 26
- Plankton 27
- Lake Washington: Uncoupling the predator-prey relationship 27
- Shellfish and harmful algal blooms 28
- Salt marshes 28
- Nearshore habitat 29
- Sensitive eelgrass and bull kelp systems 29
- Fish and other animals 30
- Salmon in a warming world 30

Implications for Ecosystem Management 32
Endnotes 34

Cover
Morning light over Commencement Bay in Tacoma showcases Mt. Rainier and the working waterfront.
Rae A. McNally

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For more information
This report is based on the "Foundation Document," which contains additional technical information. Both publications can be found on the Puget Sound Action Team Web site, www.psat.wa.gov/climatechange or the Climate Impacts Group Web site, www.cses.washington.edu/db/pubs/abstract460.shtml.

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

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Snowpack in the Olympic mountains continues to decline.

FOREWORD

Global Warming is a Fact.

Greenhouse gases heat the planet and continued warming of our climate is virtually locked into the global system far into the future.

Among thousands of scientists who study this problem, there is no disagreement on these facts. There is disagreement, however, about the specifics: how much warming will occur, where, in what time frame, and with what impacts?

How will the Puget Sound region specifically change in response to this planetary heating? That complex question is the subject of this report.

At the global level, society has never faced a problem such as this. Starting some 420,000 years ago all the way up to 150 years ago, the ambient concentration of CO_2 in the atmosphere varied between 180 to 280 parts per million by volume (ppmv) as the earth lurched between glacial and interglacial conditions. Today the concentration is about 380 ppmv and climbing.

The scientific community is reasonably certain the planet has not experienced such high concentrations of carbon dioxide (CO_2) for at least 420,000 years, and most probably not for 20 million years.

From paleoclimatological evidence, we know that over the history of the earth high levels of greenhouse gas concentrations have correlated with, and to a large extent caused, significant warming to occur, with impacts generated on a global scale.

"Even if we stopped emitting CO_2 today, warming would continue for many decades."

“It is up to all of us to ensure that we take the actions needed to prepare.”

Given the residence times of greenhouse gases in the atmosphere (several decades) and the long time it takes for the ocean to fully communicate with the atmosphere (several centuries), even if we stopped emitting CO_2 today, warming would continue for many decades.

From a policy standpoint, this disconnect between sometimes costly actions now and benefits that could be realized far in the future has prevented meaningful action, but continued delays to act guarantee that problems posed by climate change will be worse.

As we hone our knowledge of global climate change, understanding the consequences on the local level becomes more crucial so that we may prepare and adapt. Getting to answers about local impacts requires experts to zoom in and do place-based analyses and projections at the regional and sub-regional scales. This report will help us get to the needed policy discussions about how we can adapt to the coming changes.

The Puget Sound Action Team’s *2004 State of the Sound* report shows many of the indicators of the Sound’s health trending down. The human footprint is exhibited in many ways: changes in land-use/urbanization, increases in pollutants entering the Sound via river runoff and reaching estuaries and the coastal ocean, excess nutrient loading; coastal erosion and excessive armoring; and overfishing.

This footprint will be difficult to reduce given the large population growth projected for the region over the next two decades.

Climate change heightens many of the challenges facing Puget Sound. There are two major drivers of the future environmental quality in this region: the specific effects of global warming combined with the size and scale of the human footprint. This report describes probable effects of climate change, and lays out scenarios of what climate change will mean for the Puget Sound region.

The ecosystems of Puget Sound are now caught in a world of multiple stresses where the pressures of human population growth and economic development will mix with the consequences of a warmer world. This new world presents significant environmental and management challenges.

One of our most immediate needs is to develop the institutional capacity to manage both the rates and magnitudes of change on the horizon. It is the job of the scientist to provide objective information.

It is up to all of us to ensure that we take the actions needed to prepare.

Edward Miles
Co-Director, Center for Science in the Earth System, Joint Institute for the Study of Atmosphere and Ocean
University of Washington
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A sunny evening in Puget Sound.

EXECUTIVE SUMMARY

Climate Change and its Effects on Puget Sound

Profound changes have occurred in the Puget Sound environment over the past century and the next several decades will see even more change, according to this study prepared by the University of Washington's Climate Impacts Group. Based on extensive review of climate records and the current scientific literature, the report finds compelling evidence of change in the region.

> *"Profound changes have occurred in the Puget Sound environment over the past century and the next several decades will see even more change."*

Glaciers in the Cascade and Olympic Mountains have been retreating for 50-150 years. Pacific Northwest temperatures are rising faster than the global average. Puget Sound waters are warming, and river and stream flows are changing.

Human activities, primarily the burning of coal, oil and natural gas, have committed the planet to a different climate in the 21st century.

This report describes changes underway in Puget Sound, the potential future consequences of global warming, and why we need to prepare for impending change.

Projected changes include:

- **Continued increases in temperature.** Even the most conservative scenarios show the climate of the Pacific Northwest warming significantly more than was experienced during the 20th century.
- **Continued increases in water temperature.** Surface water temperature in Puget Sound and in the rivers and streams that feed into it would also increase.

- **Continued alteration of river and stream flows.** With decreased snowpack and earlier snowmelt, western Washington's low summer stream flows are likely to be further reduced, while winter stream flows rise, altering the timing of freshwater inputs to marine waters.

- **Increased flooding.** With more of the region's winter precipitation falling as rain rather than snow, flooding in Puget Sound watersheds would likely increase. If winter precipitation increases, as some models suggest, the risk of flooding would be compounded.

- **Accelerated rates of sea level rise,** especially in south Puget Sound where the effects of sea level rise are compounded by sinking land. The rate of rise in the Pacific Northwest is projected to be faster than the global average and is likely to increase both the pace and extent of the erosion and nearshore habitat loss already affecting Puget Sound shorelines.

- **Loss of nearshore habitat.** Sea level rise, temperature change and changes in nutrient availability may lead to further declines in critical marsh and coastal wetland habitats.

- **Salt marshes at risk.** Projected changes in water temperature, water salinity and soil salinity could change the mix of plant species in salt marshes and the viability of invertebrates that play a key role in the health of salt marsh systems.

- **Further pressures on salmon.** Lower summer flows and warming waters may negatively affect salmon that depend on rivers during the summer months.

- **Warmer water temperature,** potentially putting many species at risk. Plankton, the foundation of Puget Sound's food web, are sensitive to temperature change. Temperature-driven shifts in plankton could ripple through the food web, changing the composition of invertebrates, fish and mammal communities.

- **Increased likelihood of algal blooms and low oxygen concentrations in bottom waters.** Increased algal productivity in surface waters would lead to a further depletion of oxygen at depth.

> *"Because of lags in the climate system, warming and sea level rise will continue for centuries even if concentrations of greenhouse gases in the atmosphere were stabilized today."*

The scientific projections in this report are based on the best available knowledge today. The ultimate impact of climate change on any individual species or ecosystem cannot be predicted with precision. This is because impacts will depend not only on how climate changes reverberate across the food web but also on future changes in related factors, including human activities, many of which are now unknown or poorly understood.

Significant, profound change

In short, the evolutionary environment in which Puget Sound's many species of plants and animals have developed over the past 10,000 years is undergoing significant changes, changes that will likely have profound effects on the living resources of Puget Sound.

Unfortunately, climate change can't be fixed within a short period of time even if we had the funding and the resolve to do so. Because of lags in the climate system, warming and sea level rise will continue for *centuries* even if concentrations of greenhouse gases in the atmosphere were stabilized *today.*

The ultimate impact of climate change in Puget Sound depends not only on future levels of greenhouse gases, but also on choices we make in the region about dealing with climate change.

Dawn breaks over the industrial area of Fidalgo Bay near Anacortes.

We need to increase our capacity to cope with the large-scale climate impacts facing the Puget Sound region. By understanding and incorporating the projected effects of climate change into the region's planning, management and development, we may be able to increase the Sound's and our society's resilience to that change.

> *"Preparing for climate change is a high-stakes exercise in risk management."*

A few key principles can guide our management and adaptation.

We must:

- Recognize that the past may no longer be a dependable guide to the future,
- Take actions to increase the adaptability of regional ecosystems to future change,
- Monitor regional climate and ecosystems for ongoing change,
- Expect surprises and design for flexibility to changing conditions.

Preparing for climate change is a high-stakes exercise in risk management. The likelihood of substantial changes and disruption to the physical and biological environment of Puget Sound requires active and prudent management to prepare for these risks.

The simple act of firing up a fossil-fuel burning vehicle contributes to climate change. Transportation will be one of many issues on the table as policymakers grapple with ways to reduce greenhouse gases and the resulting harm a warmer climate may cause to Puget Sound.

Oil refinery in Anacortes.

Introduction

Human activities over the past 150 years have led to a changing climate in the 21st century.

By burning oil and coal and clearing land, we have embarked on an unprecedented experiment, launching the earth's climate system into unfamiliar territory. Looking at past and anticipated greenhouse gas emissions, scientists project significant changes in global average temperature, sea level and precipitation patterns. These changes will cascade through the world's ecosystems, affecting everything from coral reefs to polar ice caps and the people who depend on them.

> *"The ultimate amount of change that occurs depends on the total amount of greenhouse gases emitted now and into the future."*

What do these global changes mean for the climate in the Puget Sound region? The answers lie both in the future and in the past.

Looking into the future, we use simulation models to study changes in temperature, precipitation, sea level, snowpack and stream flow. We examine the implications for Puget Sound's circulation and water quality and for nearshore habitat and the organisms it supports.

We look to the past to evaluate how ecosystems have responded to climate fluctuations so that we can apply this knowledge to determining the consequences of future climate changes. While the past may not be a definitive guide to the future, this knowledge provides valuable lessons on how ecosystems function (or malfunction) when stressed. It is also important to recognize the influence of human activities on past responses to climate variation as future changes in climate will both shape and be shaped by the interaction of natural processes and human activities.

Looking into the past can also help us develop better management tools for the future. Climate-resilient resource management begins by considering how well current or proposed policies would perform when faced with the known climate of the historic record.

By crafting resource management policies resilient to both historic patterns of climate variability and future human-caused climate change, we can better prepare Puget Sound for an uncertain future.

The Puget Sound Basin

Figure 1: Map of the Puget Sound basin showing the main features and locations discussed in the text. Waters inside the red boundary eventually drain to Puget Sound.

A storm near the San Juan Islands.

UNCERTAIN FUTURE

Changes in Climate

Changes in the chemical composition of the global atmosphere can have dramatic effects on the global climate system, which, in turn, controls climate conditions in the Pacific Northwest.

Global climate change

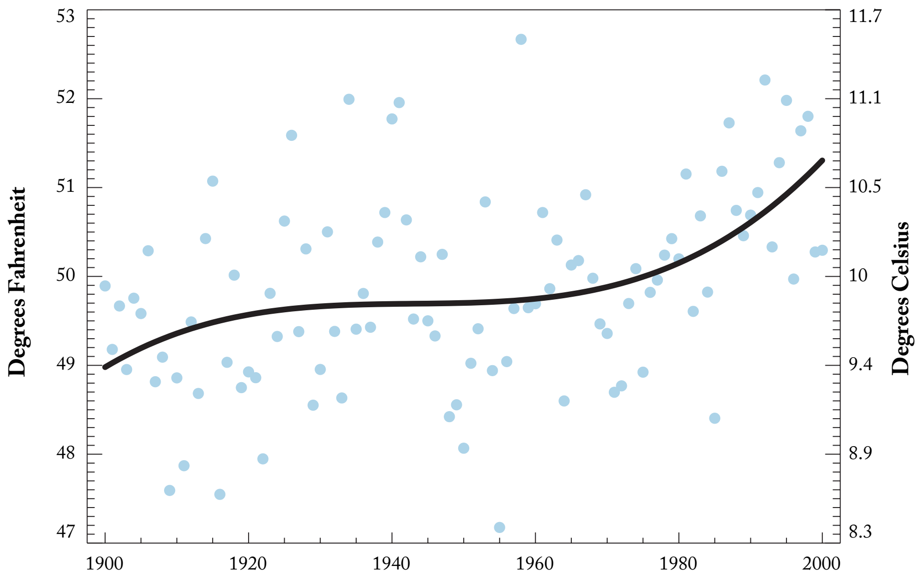
Though they comprise in total less than 0.04 percent of the atmosphere, greenhouse gases matter greatly because they absorb and give off infrared energy, thereby keeping the earth warm.[1] Geologic history shows that increasing greenhouse gases in the atmosphere leads to an increase in air temperature at the surface of the earth. During the past roughly 700,000 years, for example, variation in atmospheric concentrations of carbon dioxide between 180 and 280 parts per million by volume (ppmv) coincided with seven cycles between glacial and more mild (interglacial) conditions in which global average temperature changed by 9-14°F (5-8°C).[2] These cycles brought massive changes, including large-scale changes to the earth's physical appearance, such as ice sheets over Puget Sound and reorganizing of diverse ecosystems.

> *Methane, nitrous oxide and other greenhouse gases have also increased significantly due to human activities.*

The composition of the global atmosphere is changing again, this time faster than in past glacial-interglacial cycles.[3] During the past 150 years, human activity (chiefly the burning of coal and oil) has raised the abundance of atmospheric CO_2 32 percent to the highest levels in at least 20 million years (375 ppmv).[4] Methane, nitrous oxide and other greenhouse gases have also increased significantly due to human activities.[5]

Indeed, during the 20th century earth's average surface air temperature rose about 1.1°F (0.6°C). Most climate scientists are convinced that a substantial portion of that warming is a result of human activity. Continued warming is expected in the 21st century as a result of observed past and expected future increases in greenhouse gases. Projections for the 21st century estimate an additional increase in global average temperature in the range of 3-10°F (1.4 - 5.8°C).[6]

Because of lags in the climate system (for instance, the gradual absorption of atmospheric heat by the ocean), warming and sea level rise will continue for centuries even if concentrations of greenhouse gases in the atmosphere were stabilized today.[7] The ultimate magnitude of change that occurs depends on the total amount of greenhouse gases emitted until now and into the future.



20th Century Warming Trends

Figure 2: Average air temperature for the Puget Sound region formed by averaging observations from five representative monitoring stations. Each year's temperature is shown as a circle and the smooth curve indicates that average temperature increased 2.3°F (1.3°C) from 1900 to 2000 and 1.6°F (0.9°C) from 1950 to 2000.

20th century climate change in Puget Sound

The Puget Sound region warmed at a rate substantially greater than the global warming trend—average annual temperature increased 2.3°F (1.3°C) during the 20th century (Figure 2). Every climate record in the area showed a warming trend and rural climate stations have warmed just as much as urban stations. Much of this warming took place in the second half of the 20th century. Winter warmed 2.7°F (1.5°C) just since 1950.[8]

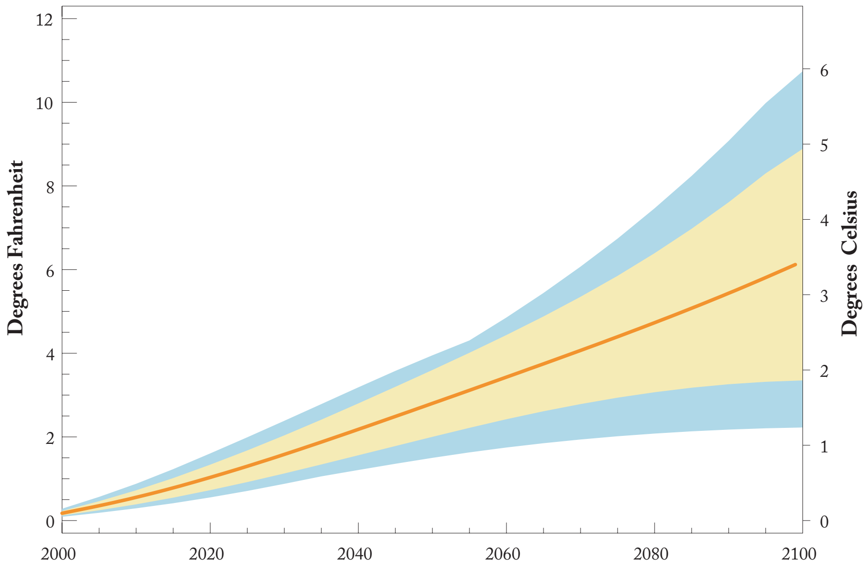
In addition to responding to changes in global climate (such as global warming), regional changes in temperature can be influenced by the atmosphere's ability to shift heat from one place to another.[9] In the Pacific Northwest, the Pacific Decadal Oscillation (PDO) is one climate pattern that shifts heat across regions of the Pacific Ocean as it cycles between warm and cool phases.[10] Some portion (perhaps one-third) of the observed Pacific Northwest warming trend in winter (between 1900 and 2000) seems to be the result of natural variation in North Pacific climate.[11] The rest of the trend in winter is probably partially due to other natural climate variations; scientists cannot yet say exactly how much each has contributed to the observed 20th century trend.[12]

In addition to trends in average conditions, several other temperature-related climatic parameters are ecologically important. Ecosystems are sensitive to how conditions vary, such as temperature variations between day and night and between seasons. The frequency and severity of extreme cold conditions, which serve to control certain pests but also can damage certain plants, can also be important. Changes in all of these parameters have been observed in the Pacific Northwest.[13]

During the 20th century, extreme cold conditions became rarer. Low temperatures rose faster than high temperatures. This is true both of day-night differences and of winter-summer differences.

While changes in temperature over recent decades have been uniformly and consistently positive across the Pacific Northwest, precipitation has fluctuated on a wide range of timescales with no clear trend over the century. Since 1950, precipitation in the Pacific

> *"The Puget Sound region warmed at a rate substantially greater than the global warming trend."*



Northwest Warming Trends

Figure 3: Projected changes in annually averaged temperature for the Pacific Northwest, compiled by considering climate scenarios from 10 global climate models each using two scenarios of future socioeconomic growth. The orange line shows the average of all the models. The blue shading indicates the range from highest to lowest, and the yellow shading indicates the range in which about two-thirds of the scenarios fall.

Northwest has generally declined. As with temperature trends since 1950, the 1977 PDO transition accounts for some, but not all, of this trend.

21st century climate change in Puget Sound

Climate models project a warming rate in the Pacific Northwest of roughly 0.2-1.0˚F (0.1-0.6˚C) per decade at least to 2050, with average warming of 1.8˚F (1.0˚C) by the 2020s and 3.0˚F (1.7˚C) by the 2040s (Figure 3), relative to 1970-1999 average temperature. Even the lowest estimated warming would change the Northwest's climate significantly more than the warming of the 20th century. Most models suggest modest (0-10 percent) increases in winter precipitation and in annual precipitation by mid-21st century; these changes are less certain than warming and will still largely fall within the range of variability observed in the 20th century.[14]

"Even the lowest estimated warming would change the Northwest's climate significantly more than the warming of the 20th century."

Characteristics of the environment that respond primarily to precipitation (such as stream flow in a river fed solely by rain) have probably already experienced the range of variability that they will experience in the next century, whereas those that respond primarily to temperature are likely to continually encounter new conditions.

Systems that are tuned to both temperature and precipitation patterns, such as the plants and animals of the Puget Sound region, are also likely to find the conditions of the 21st century different from what they have previously experienced.

The orca is one of the most recognizable symbols of the Puget Sound region. Climate change will affect orcas, which are at the top of the food chain, as well as phytoplankton, which are at the bottom of the food chain. Given the complex interrelationships among all the living components of Puget Sound, it's impossible to make detailed projects of what climate change may look like, but scientists can draw several likely conclusions. See the chapter starting on p. 26 for more details.

Glaciers such as this one, the Lyman glacier in the North Cascades, have been retreating for the past 50-150 years.

UNCERTAIN FUTURE

Changes in Snowpack and Stream Flow

Understanding how climate fluctuations affect the hydrologic cycle—the timing and amount of rain, snow, snow melt and stream flow—is fundamental to understanding climate impacts on Puget Sound.

> *"Almost everywhere in the Cascades, snowpack has declined markedly since 1950."*

Snowpack and stream flow in the 20th century

Across much of the western United States, scientists have observed hydrologic changes in the past 50 years that are consistent with the observed atmospheric warming.

These changes include:

- Reduced spring snowpack,
- Earlier spring snowmelt,
- Increased winter flow,
- Decreased summer flow.[15]

These changes, most of which have been linked by scientists to rising temperatures,[16] can lead to altered habitat for fish and other species. The observed changes also have implications for municipal and agricultural water supplies dependent on snowpack.

The hydrologic changes found throughout the West have also been observed in Puget Sound. Snowpack measurements (depth of water from melted snow, also known as the snow water equivalent or SWE) on April 1 (the most common date for observations and roughly the date of peak snowpack) show that SWE has declined markedly almost everywhere in the

Cascades since 1950.[17] These declines exceeded 25 percent at most locations, and tended to be largest at lower elevations. Compare, for example, the large decline of 33 percent observed at Tunnel Avenue (elevation 2450 feet, or 747 m) and the small decline of 4.5 percent at Rainy Pass (elevation 4780 feet, or 1457 m) (Figure 1). The trends show warming is clearly playing a role in these declines.

Freshwater inflow to Puget Sound—the total flow of all of the major rivers[18]—is an important characteristic of the Sound's marine environment. The seasonality of input and the timing and magnitude of winter and spring high-flow events influence water temperature, salinity, circulation patterns, habitat characteristics and marine life.

Freshwater inflow has changed over the period 1948-2003 in the following ways:

(a) Total annual inflow declined 13 percent owing to changes in precipitation,

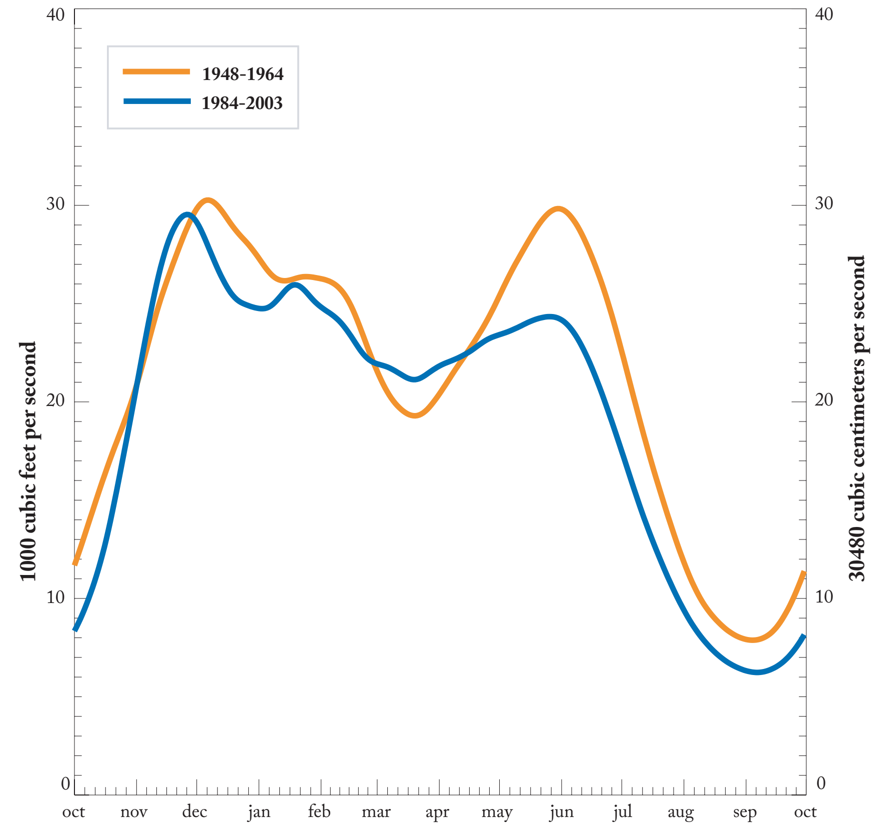
(b) The timing[19] of snowmelt shifted earlier by 12 days, or 2.1 days per decade (Figure 4),

(c) The fraction of annual flow entering Puget Sound during the summer months (between June and September) decreased 18 percent,

(d) The likelihood of unusually high daily inflow increased, despite the decline in annual inflow,

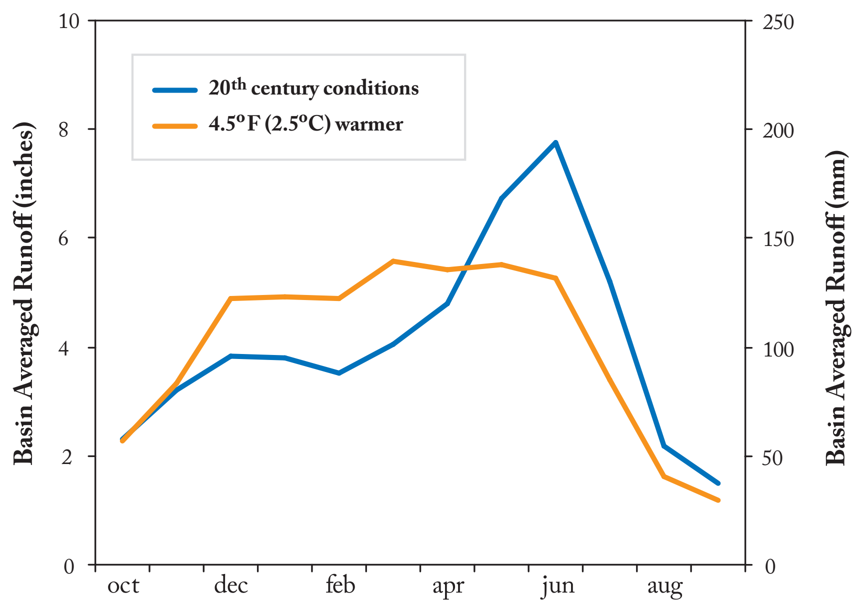
(e) The likelihood of unusually low daily inflow increased.[20]

Although it is impossible to attribute these changes specifically to global warming, and land use and flow regulation may play a role in these observed changes, it is important to note that all of these changes (except (a) which may be associated with PDO effects) are consistent with warming.[21]



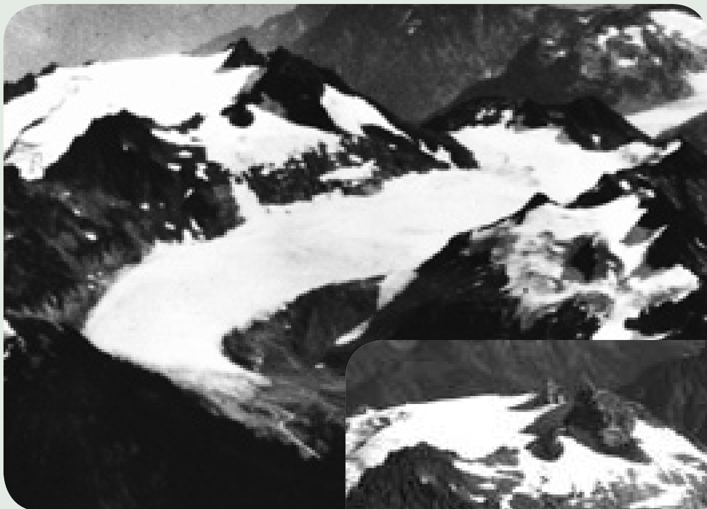
Average Daily Freshwater Flow into Puget Sound

Figure 4: Average daily freshwater flow into Puget Sound (found by adding the flow of nine of the largest rivers) for 1948-1964 (orange) and 1984-2003 (blue). Note the decline in May-October and increase in March-April.



Simulated Average Runoff for the Puget Sound Basin

Figure 5: Simulated average runoff for the Puget Sound basin, for 20th century climate (blue) and for a warming of +4.1°F (+2.3°C) (orange), which could occur as early as the 2040s but probably not until later in the century. Note the projected declining summer flow, which matches observed changes (Figure 4).



The South Cascade Glacier from the same viewpoint in 1928 (top) and 2000 (bottom). Not only has the glacier retreated substantially, leaving behind a meltwater lake, it has also thinned at higher elevations. *Figures courtesy of Dr. Ed Josberger, USGS Glacier Group, Tacoma, WA.*[81]

> *"Nearly every glacier in the Cascades and Olympics has retreated during the past 50–150 years in response to warming."*

Glaciers in retreat

Nearly every glacier in the Cascades and Olympics has retreated during the past 50-150 years in response to warming.[21]

Small glaciers are disappearing rapidly, and glacial mass is being reduced on the larger ones. While the total water input into Puget Sound from melting glaciers is minimal, glacial retreat can have important local effects.

In higher reaches of certain river basins (such as the Nooksack) and some tributaries to the Skagit, melting glaciers provide a substantial portion of stream flow in late summer. This is also true for the Nisqually River, which is fed by receeding glaciers on Mt. Rainer.

Glaciers also have significant local effects on stream temperature and water supply for aquatic plants and animals. Significant reductions in glacial input to streams would dramatically alter vulnerable aquatic habitat.

Snowpack and stream flow in the 21st century

The seasonal timing of freshwater inflows to Puget Sound is extremely sensitive to temperature. The primary consequences of regional warming scenarios are:[23]

- Reduced winter snowpack in the mountain portions of the basin,
- Greater stream flow in winter (more precipitation falling as rain and less as snow),
- Earlier occurrence of peak runoff,
- Reduced summer flows.

For a warming of +4.1˚F (+2.3˚C), which could occur as early as the 2040s (but probably not until later in the century), October through March runoff increases by about 25 percent and April through September runoff decreases by 21 percent (Figure 5). The consequences of these changes for Puget Sound circulation and ecosystems are described in the following sections.

Flooding

Higher winter temperatures are likely to increase the chance of flooding in Puget Sound as more winter precipitation falls as rain rather than snow in moderate elevation mountain areas, such as the Cascades.[24] If winter precipitation increases, as some models suggest, the risk of flooding would be compounded.

Flooding increases in free-flowing rivers are a concern because management of high flows is not an option. In managed systems high stream flows can be controlled to a certain extent. Most urban areas located on river mouths are partially protected by upstream flood-control reservoirs or were developed sufficiently far above the waterline to protect against flooding. Agricultural districts in river deltas (such as the Skagit) are partly protected by dikes. However, increases in natural flows could still cause increased flooding in managed systems when these protective measures are overwhelmed.

Western Washington is famous for its rain. With a warmer climate, however, scientists believe more of our precipitation will fall as rain rather than as snow at higher elevations. That means a higher chance of flooding and other problems associated with more freshwater entering salty Puget Sound.

Tide changes expose shells on the beach at Potlach State Park on Hood Canal. *Rae A. McNally*

Changes in the Waters of Puget Sound

Puget Sound supports a stunning diversity of life within and around its waters. Fluctuations in climate and sea level play a role in determining the suitability of these habitats through their influence on circulation and water properties.

Sea level rise

Sea level naturally rises and falls over the course of hours, months and years. Sea level fluctuates most in the twice-daily tides. Variations in atmospheric pressure and wind patterns produce sea level changes (up or down) on timescales of days to decades. Local land movements affect local sea level on timescales of centuries or suddenly during earthquakes.

In addition, global sea level has been increasing at an estimated rate of 4-8 inches over the 20th century (1.0 to 2.0 mm/yr) as a result of both the warming of ocean waters, which causes thermal expansion, and the melting of glaciers, small ice fields and polar ice sheets.[25]

Complex geological factors produce different rates of sea level rise across the Puget Sound region.[26] Land is sinking in much of Puget Sound, with rates ranging from zero in the eastern Strait of Juan de Fuca and north Puget Sound to more than 8 inches per century (2 mm/yr) in south Puget Sound.[27] Thus, net local sea level rise in north Puget Sound is close to the global average, and is up to double the global average in south Puget Sound.

Future global sea level rise is likely to accelerate as a result of human-caused global warming, with changes likely in the range of 4-35 inches (0.09-0.88 m) during the 21st century. This is one of the best understood and predictable components of future climate change.[28] Some climate models suggest additional sea level rise in coastal waters—which would affect Puget Sound—associated with changes in winds, on the order of an additional 8 inches (20 cm).[29] Adding these changes to the geological changes, it appears likely that sea level rise in Puget Sound will proceed at least as rapidly as, if not faster than, the global average rate of increase with rates varying around the Sound, depending on land uplift or sinkage (Figure 6).

Circulation in Puget Sound

The circulation of Puget Sound—the meeting and mixing of saltwater from the Pacific Ocean and freshwater from the region's many rivers—is strongly influenced by the Sound's salinity, temperature and geography.

The Sound is a glacially carved basin separated from the Strait of Juan de Fuca by a shallow (144 feet, or 44m) sill at the north end of Admiralty Inlet that limits the exchange of water between the Sound and the Strait. The Sound's circulation is dominated by:

- The addition of freshwater at the surface, which generally flows seaward and must be balanced by inflow of salty water at depth,

- Tidal stirring, especially at the sill at Admiralty Inlet. Tidal stirring can be a significant force, pushing as much as 60 percent of the surface waters to great depth in the main basin.[30]

The Whidbey sub-basin receives freshwater from the Skagit River, the largest in the Sound, and usually has sharply stratified or layered waters with a shallow (about 30 feet, or about 10 m), surface layer of relatively fresh water. The numerous inlets of the south Sound often have warm surface water in summer. Hood Canal has a shallow sill of 160 feet (50 m) at the mouth and is also long, deep and narrow, resulting in the slowest circulation of the sub-basins. This slow exchange causes the southern end to become especially susceptible to periods of hypoxic or oxygen-deprived conditions at depth.

“Global sea level has been increasing at an estimated rate of 4–8 inches over the 20th century.”

Changes in timing of freshwater input may affect the circulation, stratification and mixing of the Sound, but the subject is largely unstudied. The higher freshwater inputs during certain climatic periods (such as the cool phase PDO, 1947-1976) cause the inflow of salty water to be shallower than under drier conditions when the inflow is nearer the bottom.[31] The decrease in freshwater inflow to the Puget Sound-Georgia Basin during the drought of 2000-2001 resulted in a four-fold reduction in the outflow of surface water through the Strait of Juan de Fuca.[32]

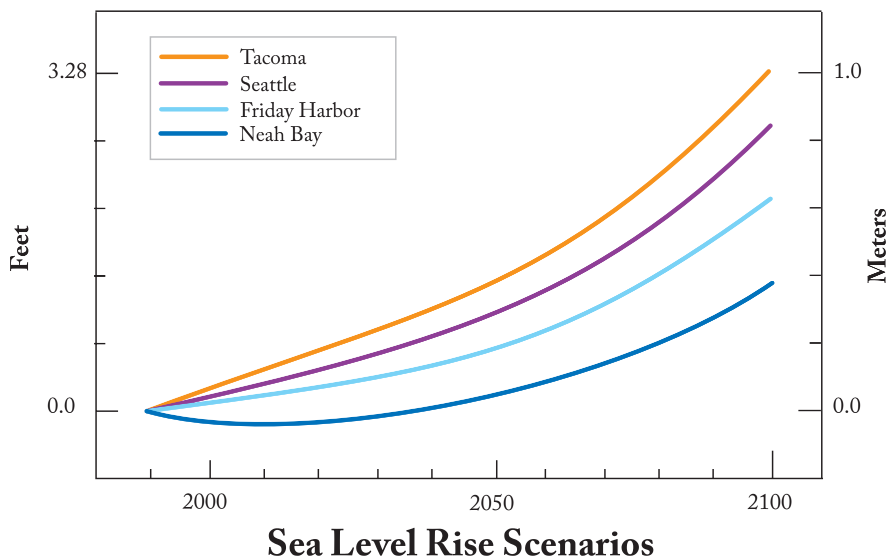


Figure 6: Future sea level rise scenarios for various locations in Puget Sound. These sea level rise curves account for projected global sea level rise, the increased rate projected for the NE Pacific and the sinking of local land. The degree of sea level rise projected at Tacoma for 2050 (about 1.3 feet or 0.4 m) would not occur at Seattle until around 2060 and at Friday Harbor until around 2080. Depending on the various climate sensitivity factors and response option assumptions, the sea level rise scenarios could be 20 percent to nearly 200 percent of the mid-range scenario depicted.[82]

Detailed studies using model simulations are needed and should include human-influenced changes such as land use and water management. Some of the tools needed for a more detailed assessment have already been assembled as part of the Puget Sound Regional Synthesis Model (PRISM) research effort at the University of Washington.[33]

Washington state coastal beaches.

Coastal upwelling

The characteristics of saltwater coming into Puget Sound are determined in large part by climate conditions along Washington's ocean coast.

Summertime winds from the north drive coastal upwelling along the Pacific coast, bringing cold, salty and nutrient-rich deep water to the surface. Periods of weak or southerly winds following upwelling events frequently sweep the upwelled waters along the coast into the Strait of Juan de Fuca. The strength and timing of coastal upwelling varies considerably from weeks to decades. How the upwelling of biologically important nutrients changes as a result of global warming will be influenced by future changes in large-scale atmospheric circulation and local winds, although current climate model simulations suggest that crucial wind patterns are relatively insensitive to global warming.[34]

> *"Of the water quality problems identified in the Puget Sound basin in 2004, 20 percent were related to river temperatures that exceeded critical threshold values."*

Further studies of upwelling are needed to more accurately predict changes in upwelled nutrients.

Water quality

Key properties that characterize the physical and biological function of fresh and marine waters in Puget Sound include water temperature, salinity, density, stratification (layering), dissolved oxygen, nutrients and fecal coliform levels. These water properties are influenced by fluctuations in Pacific Ocean water, freshwater inputs, and local weather conditions. While human influences are often the primary cause of water quality degradation, climate variability and change may worsen water quality problems when these changes exceed the buffering capacity of the system.[35]

Water temperature

Water temperature is an important factor controlling the suitability of habitats for freshwater and marine organisms and physical, biological and chemical processes important in the food web. Many Puget Sound species, such as salmon, oysters and groundfish, depend on cold water. Of the water quality problems identified in the Puget Sound basin in 2004, 20 percent were related to river temperatures that exceeded critical threshold values.[36]

Many factors contribute to increased water temperature in freshwater and marine systems. Climate plays a role in determining water temperature via its influence on air temperature, the temperature of stream and river inflows, and the degree of stratification in marine systems.

Information on trends in water temperature for freshwater and marine water systems in the Puget Sound basin is limited, but there is evidence of warming during the 20th century. Long-term records show Lake Washington warming substantially since the 1960s.[37]

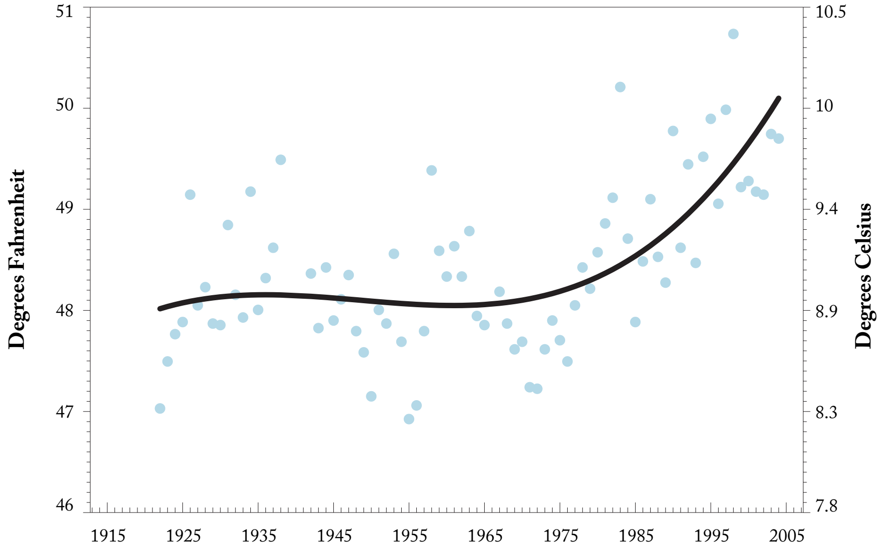
There are no long-term measurements of sea surface temperature in Puget Sound itself, but there are nearby records that indicate warming over the 20th century. Measurements at the Race Rocks lighthouse in the Strait of Juan de Fuca near Victoria, BC date back to 1921 and indicate decadal-scale fluctuations and a long-term warming trend of 1.7˚F (0.9˚C) since 1921 and 1.8˚F (1.0˚C) since 1950 (Figure 7). Research using the internal growth rings of geoduck shells as an indirect record of sea surface temperature in the Strait of Juan de Fuca found the 1990s to be the warmest decade in a record dating to the 1840s for March through October sea surface temperatures in the Strait of Juan de Fuca.[38] Sea surface temperature variations studied over shorter time periods during the late 1990s show a correlation with air temperatures.[39]

Looking toward the future, global warming is almost certain to lead to additional warming of the surface waters of Puget Sound and its tributary rivers as a result of the projected increases in regional temperature and decreases in summer stream flow.

Salinity

Sea surface salinity or saltiness is an important determinant of water density, which in turn influences circulation patterns and marine habitat conditions. Major influences on sea surface salinity in Puget Sound marine waters are: the salinity content of Pacific Ocean water entering through the Strait of Juan de Fuca, and the amount and timing of freshwater inflows from Puget Sound basin rivers and streams.

Unfortunately, no long-term records of salinity exist for Puget Sound and trends related to climate cannot be calculated, but measurements taken in the 1990s indicate that years with lower stream flows have coincided with higher sea surface salinity and high stream flow with low salinity, as expected.[40] Records at Race Rocks since 1936 show that fluctuations in salinity are correlated with Puget Sound-area winter precipitation. Salinity has slightly decreased during this time, although this salinity trend cannot be explained by the trend in precipitation.



Sea Surface Temperature

Figure 7: Average annual sea surface temperature at Race Rocks, near Victoria, BC. Each year's temperature is shown as a circle and the smooth curve indicates a long-term warming trend of 1.7°F (0.9°C) since 1921 and 1.8°F (1°C) since 1950.

It is likely, then, that the observed changes in stream flows noted previously have increased salinity in summer and decreased it in winter, and projected future changes in freshwater inputs would cause larger changes of salinity.

Stratification

A stratified or layered water column has properties (density, nutrient content, etc.) that change rapidly with depth. Stratification occurs in waters where mixing, such as by winds and tides, is low. The degree of stratification affects upwelling of nutrient supplies to surface waters, phytoplankton growth, the availability of dissolved oxygen to waters at depth, and pollutant flushing.[41]

Stratification in marine waters is largely driven by water temperature and salinity. Cold and/or salty water is denser and tends to sink, while warmer and/or fresher water lies above the colder layer. As a result, freshwater is more difficult to mix down into the water column and water rich in dissolved oxygen remains confined to the surface.

In many areas of Puget Sound, variations in salinity resulting from freshwater input from nearby rivers are the main control on stratification.[42] Increasing solar radiation, weak winds, and weak water circulation also increase stratification.[43] The reduced freshwater inflow during the 2000-2001 drought resulted in a 56 percent average reduction in stratification in greater Puget Sound.[44]

In winter months, projected increases in stream flow would increase stratification in Puget Sound. In summer months the expected change is less clear—there will be some cancellation between increased surface water temperature (which would increase stratification) and the increased surface salinity resulting from reduced stream flow (which would decrease stratification). Which one of these processes dominates will likely vary regionally in the Sound depending on circulation processes in different locations.

> *"It seems probable that dissolved oxygen levels at depth could decrease, increasing hypoxic conditions in bottom water."*

Dissolved oxygen

The amount of dissolved or free[45] oxygen in water helps determine habitat suitability for fish and other organisms. Deep waters extremely low in dissolved oxygen can stress or even kill fish. The amount of dissolved oxygen (DO) can be reduced by a variety of factors, including:

- Higher water temperature,
- Stratification of the water column, which confines low-DO water at depth,
- Freshwater inflows with high organic content or low DO,
- Coastal upwelling of low-DO deep water at the entrance to the Strait of Juan de Fuca,
- Decomposition of organic material.[46]

Low DO is common in the sub-surface waters of Puget Sound (deeper than approximately 65 feet, or 20 m), with 56 percent of monitoring sites reporting DO below the threshold of 5 ppm (5 mg/L).[47] This threshold is considered to be a concentration that causes stress in biological organisms.

Studies have linked periods of low DO in the 1990s with reduced flushing of Puget Sound waters and reduced freshwater inflow. Trends in DO have not emerged since routine monitoring began only in 1993. Thus more studies are needed to more fully understand how projected climate change may affect DO levels in Puget Sound's waters.

Evaluating the factors controlling DO and the likely direction of change that each might experience in a warming climate, it seems probable that DO levels at depth could decrease, increasing hypoxic conditions in bottom water. This is because increased surface populations of marine plants and animals (resulting from higher water temperature and greater winter stratification) would result in increased consumption of oxygen at depth when they die and sink.

Modeling studies should be conducted to determine the relative importance of changing climate influences (for example changes in winds, cloudiness and freshwater inputs) versus changing nutrient inputs from septic tanks, fertilizer runoff and land use practices.

Nutrients

Nutrient inputs such as nitrogen and phosphorus have important effects on the biological and chemical processes necessary to support freshwater and marine species in Puget Sound. Too few nutrients can limit primary productivity while too many nutrients can lead to excess primary production and oxygen depletion via decomposition of the excess organic matter. Nutrient-rich inputs into Puget Sound include stormwater runoff, industrial waste discharges, failing septic systems, tributary inflows and coastal upwelling. Surface water nutrient levels are also influenced by stratification and organic productivity (decreasing with increased stratification or productivity).

Monitoring of nitrogen and phosphorus in freshwater rivers and lakes in the Puget Sound area began in 1991. Most of the 20 sites monitored had no significant trends during the 1990s, but three had declining trends in total nitrogen and five had increases in total phosphorus.[48] In the Sound, three locations —Budd Inlet, south Hood Canal and Penn Cove—have been identified as exceptionally sensitive to eutrophication,[49] which is a process where water bodies receive excess nutrients that stimulate excessive plant growth (algae and submerged aquatic vegetation). This enhanced plant growth, often called an algal bloom, reduces dissolved oxygen in the water when dead plant material decomposes, and can cause other organisms to die. Many more sites around the Sound also have been identified as sensitive to eutrophication.[50]

Regional climate change will affect surface mixed layer nutrient levels via changes in sea level (increased leakage from septic systems), biological productivity, and freshwater inflow. Future nutrient levels will also depend on changes in sources related to human activities, such as agricultural and home gardening practices.

The overall impact of climate change is hard to project because of incomplete knowledge of the relative importance of potentially competing influences. Freshwater inflow, for example, has the potential to both increase and decrease nutrient concentrations. Increased runoff, which could increase nutrient delivery, results in increased stratification of the Sound and therefore increased depletion of nutrients by phytoplankton. Really high runoff in some urban areas may overwhelm sewage treatment plants, leading to more frequent sewer system overflows and therefore increased nutrient concentrations. The overall change will hinge on the balance among these various effects.

Fecal coliform and other pollutants

Fecal coliform is used as an indicator of potentially harmful bacteria and viruses from human and animal wastes. Fecal coliform enters fresh and marine water bodies primarily through stormwater runoff, failing septic systems, combined sewer overflows, livestock operations, and contaminated freshwater inputs from rivers and streams. Fecal coliform is a major concern because it can contaminate beaches and shellfish harvesting in Puget Sound. Forty-one percent of water quality problems identified in the Puget Sound basin in 2004 were related to fecal coliform bacteria.[51]

Livestock runoff can contaminate nearby waters. Pictured here, a Midwest farm.

Recent trends in fecal coliform levels in Puget Sound and nearby freshwater systems have been mixed, with some showing improvements and some showing deterioration over time. A climate connection has been suggested by the Washington Department of Ecology. During high precipitation periods between November 1998 and January 1999, and in November 1999, fecal coliform counts were particularly high due most likely to increased runoff into nearshore waters.[52]

Future contamination by pollutants such as fecal coliform will be driven largely by future strategies for handling human and animal waste. Climate change could exacerbate problems with fecal coliform contamination because increased winter rains would likely lead to more stormwater runoff and combined sewer overflow events, as well as increased septic system leakage resulting from sea level rise.

The Tacoma waterfront at sunset. *Courtesy City of Tacoma*

UNCERTAIN FUTURE

Consequences for Marine Ecosystem Structure and Function

Climate warming will shape the Puget Sound ecosystem from both the bottom-up (via impacts on phytoplankton and other marine plants that comprise the base of the food web) and the top-down (via direct impacts on top predators such as salmon and marine mammals). Taken together, these changes can be dramatic. In the coastal ocean, for example, broad reorganizations of the marine ecosystem have been associated with the subtle decade-to-decade changes in climate associated with the PDO.[53] This has resulted in salmon in the coastal waters of Washington, Oregon, California, British Columbia and Alaska returning in relatively large or small numbers, depending on the phase of the PDO.[54]

> *"The ultimate impact on each individual species that calls Puget Sound home will depend on how each of these changes reverberates across the food web."*

Future climate-related changes in the environment will be accompanied by changes in other factors such as human activities that are also very difficult to predict. The ultimate impact on each individual species that calls Puget Sound home will depend on how each of these changes reverberates across the food web, how each change interacts with every other change, and on the ecosystem's ability to adapt to a rapidly changing chain of estuarine and oceanic conditions.

The complex interrelationships among all of the living components of the Puget Sound ecosystem make detailed projections of the changes that may result from global warming impossible. In the following sections, we suggest how the projected changes already described (in water temperature, freshwater inflow, sea level rise, etc.) may affect individual components of the ecosystem, specifically plankton, fish and other animals, nearshore habitat and Puget Sound salmon.

Plankton

The base of the food chain includes benthic or bottom-dwelling algae and tiny floating algae called phytoplankton. Major changes in these populations have been observed over the last several decades that may have resulted from changes in climate and/or human influences.[55] Climatic influences on phytoplankton include variations in temperature and other water properties.

In Puget Sound, variations in temperature may be more important for phytoplankton than variations in freshwater input and mixing.[56] Thus a warming climate may increase surface productivity. Warmer temperatures would also alter the rates of processes in deep water, for example, increasing respiration,[57] which would decrease the concentration of oxygen in deep waters. Not only do changes in average temperature matter; changes in the amount that temperature varies over the year in any one location will also shape future ecosystem characteristics.[58]

Higher future levels of atmospheric CO_2 will also influence these dynamics. With uptake of CO_2, ocean water has become more acidic and will continue to do so.[59] This will alter water quality and consequently favor those plankton, fish and other marine organisms that tolerate more acidic water. Acidification will also make it more difficult for two important types of plankton—coccolithophores and foraminifera—to form their calcite shells. These changes are likely to be important to the food web, but in ways scientists cannot entirely predict.

Lake Washington: Uncoupling the predator-prey relationship

In the freshwater environment of the region's lakes, stratification is driven by temperature and there are indications of important changes linked to the effects of climate warming on stratification.

Long-term records show Lake Washington warming substantially since the 1960s.[60] Combined with variability in climate associated with the Pacific Decadal Oscillation (PDO), a warming climate has extended the period of summer stratification in Lake Washington from 1962 to 2002 by 25 days, mainly through earlier spring stratification (16 days).[61]

Warmer temperatures in the future may further increase the duration of summer stratification in Lake Washington.

In Lake Washington, the spring phytoplankton bloom (period of enhanced plant growth) has been occurring earlier in the year, reflecting the earlier timing of the spring transition to stratified or layered water conditions.

Some zooplankton species (the tiny creatures that feed on phytoplankton) have adjusted to this change in timing while others have not. For example, the bloom timing of the species *daphnia* has not changed. This has resulted in a growing gap between the timing of the spring peak of zooplankton and that of the phytoplankton on which they depend.[62]

The shift in this previously well-timed interaction between a predator and prey may have severe consequences for the entire ecosystem if climate continues to warm.

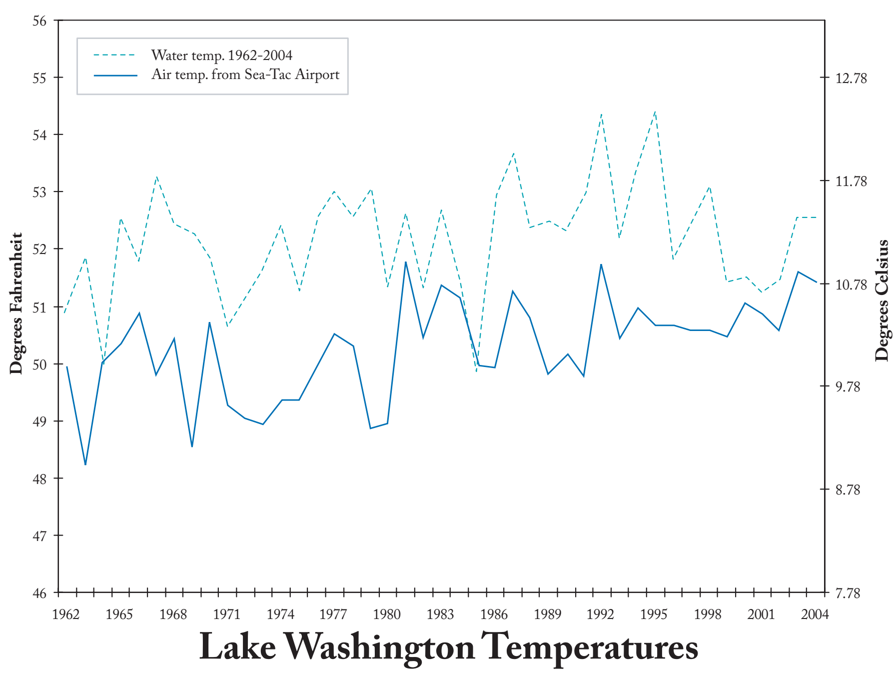


Figure 9: Observed trends in Lake Washington temperatures. The solid line shows annual average water temperature (0-200 feet, or 0-60 m) from 1962 to 2004. The dashed line shows annual average air temperatures from Sea-Tac Airport for comparison.[82]

Puget Sound shellfish. *Rae A. McNally*

Shellfish and harmful algal blooms

Puget Sound is one of the largest shellfish-producing regions in the United States.[63] Puget Sound shellfish are vulnerable to contamination by the toxics produced by harmful algal blooms. Toxic blooms can lead to closure of commercial and recreational shellfish beds to protect the public against paralytic shellfish poisoning (PSP), a potentially fatal illness caused by eating contaminated shellfish, and domoic acid poisoning (DAP), which can cause temporary or permanent memory loss.

Concentrations of toxins in Puget Sound shellfish and the geographical scope of shellfish closures have increased over the past four-to-five decades.[64] There has been a slow progression of PSP toxins from northern to southern areas of Puget Sound. Since the 1980s, the frequency of detection of PSP toxins has increased in the southern basins of Puget Sound, an area containing the region's most productive shellfish beaches. Public beaches can also be affected by these pathogens. DAP has only been observed much more recently; the first closure of a Puget Sound beach due to DAP occurred at Fort Flagler (near Port Townsend) in 2003. The most recent inland waters DAP-related shellfish closure took place in September 2005 in Sequim Bay.

Growing human development of the Puget Sound region is likely a major contributor of the recent increases in PSP toxins. Increased nutrients (via activities such as aerial forest fertilizing, sewage outfalls and agricultural runoff) can provide more favorable growth conditions for the algae producing PSP toxins. Those algae also respond favorably to stratified conditions, while the algae that produce domoic acid are thought to be favored by well-mixed environments and warmer temperatures.[65]

Climate change could increase the viability of some organisms responsible for harmful algal blooms in Puget Sound. Increased winter stratification of water may encourage more PSP-causing algae. Warmer temperatures may yield more DAP-causing algae, but increased winter stratification may have the opposite effect. The ultimate magnitude and frequency of future harmful algal blooms will depend on environmental changes and human use of Puget Sound.

Salt marshes

Salt marshes are highly productive habitats found near river mouths where fresh and saltwater mix. Salt marshes support a mix of plant and animal species, including shrimp, crabs, salmon, terns and herons. The plants filter suspended sediments and nutrients, regulate dissolved oxygen in the water column, stabilize bottom sediments, and even reduce flooding by retaining stormwater during high-flow periods.

Salt marsh growth and distribution are affected by sea level, salinity, temperature, freshwater inputs, tidal flooding, and the physical characteristics of the landscape. Human factors, predominantly draining, diking, dredging, filling, erosion, pollution and dams, have contributed to an estimated 73-percent decline in salt marsh habitats since the mid-1800s with the most acute losses (near 100 percent) in heavily urbanized central Puget Sound.[66]

During the modest sea level rise of the 20th century, most remaining salt marshes were able to keep pace through accretion or the accumulation of sediments, generally rising as a result of sediment capture.[67] Twenty-first century sea level rise may lead to further loss of salt marsh habitat, particularly where land areas are already sinking (i.e., central and southern Puget Sound) and/or where sediment supply is reduced or where upland migration of marshes is prevented by shoreline armoring, coastal development or natural bluffs, for example.

Nearshore habitat

Sea level rise will affect many physical processes important for determining nearshore habitat characteristics above and beyond salt marsh conditions. Sea level rise is likely to increase both the pace and extent of Puget Sound shorelines threatened by slow, chronic erosion. At the same time, landslides along Puget Sound bluffs may increase because of the heavier winter rainfall projected by nearly all of the global climate models. These two changes would likely exacerbate each other.

The ultimate consequences for nearshore habitat will depend in a large part on how communities and citizens respond to these changes. Increased coastal armoring (e.g., bulkhead installation) can provide short-term local shoreline protection but is likely to have negative downstream effects on nearby beaches and limit the adaptability of wetland and eelgrass habitat.[68]

Climate change will also affect biological processes important for nearshore habitat. Changes in water temperature, water salinity, or soil salinity beyond the tolerance of certain plants could change the mix of plant species in salt marshes and the viability of invertebrates (e.g., crab, shrimp and sponges) that play a key role in the health and functioning of nearshore systems. Changes in precipitation could change nutrient loading and sediment accumulation. Increases in atmospheric CO_2 levels may stimulate growth in some nearshore plants.[69]

The degree to which any of these changes affect Puget Sound nearshore areas will vary with the specific characteristics of the ecosystem, its location in the Sound, its freshwater sources and the dynamics of the Sound in that particular area.

Diver surrounded by eelgrass. *John Southard*

Sensitive eelgrass and bull kelp systems

Eelgrass, found in shallow water to a depth of about 22 feet (around 7 meters), provides valuable habitat and food for many marine species, including herring, juvenile cod and salmon, sole, flounder and invertebrates. Eelgrass also provides valuable erosion control along the Puget Sound coastline by absorbing wave energy. As with salt marshes, human factors have reduced eelgrass beds by perhaps 33 percent.[70]

Climate-driven factors influencing eelgrass are sea level, temperature and salinity. These factors help determine where and how abundantly eelgrass grows: it prefers high salinity and low summer temperatures.[71]

Lower spring stream flow increases Puget Sound salinity and decreases suspended solids, factors that tend to increase eelgrass growth. Studies in Puget Sound have found that optimal eelgrass productivity occurs within a narrow range of temperatures—between 41-46˚F (5-8˚C).[72]

Climate warming may favor eelgrass growth by shifting stream flow from the growing season (spring and summer) to the winter, but these benefits would be minimized if water temperatures regularly exceed 59˚F (15˚C)—the temperature at which eelgrass becomes stressed[73]—or if rising seas result in a sufficient reduction in available light for photosynthesis.

Increasingly armored shorelines also could reduce areas of eelgrass through changes in sediment delivery and increased water depth.

Warmer water temperatures may also negatively affect Puget Sound kelp, another important subtidal plant that provides critical nearshore habitat. On the other hand, both eelgrass and bull kelp may benefit from higher concentrations of atmospheric CO_2. Laboratory experiments indicate that when exposed to seawater containing higher levels of CO_2, growth increases.[74]

Additional study is needed to assess how these competing factors will ultimately affect eelgrass and bull kelp systems.

E. Fork of Chimacum Creek. / Al Latham.

Salmon in a warming world

All seven species of Pacific salmon and anadromous bull trout live within the Puget Sound Basin. In most river basins, wild populations are severely depleted and hatcheries operate to supplement wild runs in order to sustain salmon fisheries. Several stocks have been listed or are being considered for listing under the federal Endangered Species Act.

Although the picture is generally bleak, some positive exceptions can be found. Over the last three decades, for example, the chum salmon populations of Puget Sound have increased to the point that they are now the most abundant salmon species in the region.[79]

The causes of salmon decline have been summarized as the "four H's": Habitat, Hydropower, Harvest and Hatcheries. Climate is an important factor in anadromous fish habitat at every stage of their lifecycle. Because of differences in life history and habitat among the different stocks and species of salmon, steelhead and trout, the same climate events can affect different stocks and species in different ways.

For example, the same ocean conditions have been good for some stocks and bad for others. According to data collected by the Washington Department of Fish and Wildlife's science division, for example, marine survival rates for south Puget Sound coho have plummeted in recent years while marine survival rates for coho in the main basin of Puget Sound and Hood Canal have been relatively high.

The general picture of climate change for the Puget Sound—increased winter flooding and decreased summer and fall stream flows, along with elevated warm season stream and estuary temperatures—would be especially problematic for instream and estuarine habitat for salmon in the Puget Sound region.

Although most impacts of climate change look negative for salmon, a positive change could result from warmer stream temperatures in periods (generally during the cold season) that are now cooler than is optimal for rearing juvenile salmon and/or incubating eggs. Positive changes such as this, which apply to individual life history stages, could be cancelled out by negative changes prevalent during other periods of the salmon's life.

Future coastal oceanographic conditions could conceivably change in positive ways for salmon, but the nature of these changes is highly uncertain because of the close dependence on uncertain future changes in coastal winds.

Fish and other animals

Fish and other animals will be affected by climate change in many ways—directly via changes in habitat and indirectly via changes in the availability of food.

Temperature is a dominant controlling factor of growth rates of most cold-blooded marine organisms. Increasing water temperatures can increase growth rates, providing many benefits, but only to a certain point.[75] Temperatures that are too warm can stress an organism, causing decreased growth and survival and weakened immune systems, which have been linked to disease epidemics in marine populations (e.g., sea urchins) and seabirds and disease-related marine mammal strandings.[76]

The consequences of warmer temperatures may be especially severe for species unable to seek out cooler temperatures, especially at vulnerable life stages. For this reason, increasing water temperatures above the optimum level for stationary shellfish, for example, could have more severe impacts than increasing water temperatures above the optimum level for salmon that could presumably move to pockets of cooler water.

Still, salmon experience thermal barriers to migration when stream and estuary temperatures reach approximately 70-72°F (21-22°C).[77] The number of days when water temperatures in the Ship Canal exceeded 68°F (20°C) in summer has clearly increased since 1974. From 1974 to 1981, the number of summer days when temperature exceeded the threshold ranged from a low of 15 to a high of 48. All summers from 1983 to 1998 had more than 48 days warmer than the threshold, with an average of 68 high-temperature days and a maximum of 87 in 1992.[78]

Many migratory birds pass through Puget Sound for food and shelter on their routes. They will be affected here and elsewhere as climate change alters the availability of food and habitat.

Jennifer Vanderhoof

Small marine organisms such as the feather duster worm could be affected by climate change in many ways—directly via changes in habitat and indirectly via changes in the availability of food. The consequences of warmer temperatures may be especially severe for species unable to seek out cooler temperatures, especially at vulnerable life stages.

Puget Sound Council members and PSAT staff tour the state's most productive clam-growing area, Oakland Bay (near Shelton). *Scott Redman*

CONCLUSION

Implications for Ecosystem Management

A first step in crafting resource policies for dealing with climate change is to ensure that policies perform well in the face of historic climate variability.

> *"We must recognize that the past may not be a dependable guide to the future."*

An important set of questions to pose is: how well has this resource policy fared in the face of past climate variations? What types of climate variations present the greatest risk to the resource of interest? Which management or policy options would reduce those risks? The answers to these questions can guide development of policies that are resilient and adaptable to a wide range of climate conditions.

This step is necessary but not sufficient for preparing for climate change. It is also important to recognize that the past may not be a dependable guide to the future. Planners should examine how resource management policies would perform in the future as key aspects of climate (e.g., maximum summer temperatures, sea level) change.

For example, stormwater planning, which relies on historical data, may underestimate the chance of intense precipitation events in a warmer climate, resulting in more frequent than anticipated combined sewer overflow events and pollution of Puget Sound waters. Similarly, habitat conservation plans concerning coastal wetlands need to include projected sea level rise and perhaps allow for inland expansion through rolling easements as has been done elsewhere.

A related challenge is to maintain or increase the resilience of the Puget Sound ecosystem. The fact that it is impossible to project exactly what climate change means for a certain species of fish or crab means that it will be very difficult, if not impossible, to engineer resource management to match anticipated climate conditions. It may be more effective to maintain the ecosystem's capacity to adapt to future changes as they come.

This could mean, for example, preserving wild salmon population diversity through the conservation and restoration of interconnected freshwater and estuarine habitat and the proper management of hatchery programs. This also could mean preserving the ability of wetlands to migrate inland to ensure adequate nearshore habitat for juvenile salmon and other creatures.

Vigilantly monitor change

Effective management and planning requires we put systems in place to monitor regional climate and ecosystems for ongoing changes. The effects of climate change may initially be subtle and difficult to disentangle from the changes wrought by humans and by natural climate variations, but without monitoring and accounting for these changes we will fail to understand the root causes of changes in the Sound or the ways in which current conditions differ from those experienced in the past.

Analysis of the causes of hypoxia in Hood Canal, for example, needs to include observed trends in temperature and runoff—an approach that is being taken by the Hood Canal Dissolved Oxygen Program.[80] Future management decisions will be best served by an informed understanding of how global climate change is manifesting in changes in Puget Sound climate, hydrologic conditions and ecosystems.

Expect surprises

It is essential to expect surprises and design for flexibility to changing conditions. We should design contingency planning into management guidelines to ensure that ongoing adaptation to unexpected (or uncertain) conditions can occur without requiring additional policy intervention.

Preparing for climate change can be thought of as an exercise in risk management. Projected regional climate change shows a risk of substantial changes to the physical and biological environment of Puget Sound and prudent resource management will prepare for these risks. By assessing the outcomes associated with different resource management activities under various climate change scenarios, planners and decision makers can prioritize their adaptive strategies.

"It is essential to expect surprises and design for flexibility to changing conditions."

When relatively little is at stake, plans could be prepared under a conservative or best-case climate change scenario. When more is at stake, or when climate impacts are likely to have irreversible ecosystem consequences, planners should consider a mid-range or worst-case scenario.

Over the coming decades, global warming will bring new change to the environment of Puget Sound. By starting now to plan for these changes, we can build the political, socioeconomic and ecological capacity required to prepare for and cope with climate impacts in the Puget Sound region.

ENDNOTES

1 Human-caused emissions of sulphate aerosols (produced by burning high sulfur coal) have to-date likely offset a substantial fraction of greenhouse warming by reflecting sunlight back to space. While greenhouse gases are well-mixed in the atmosphere with typical lifetimes of decades to centuries, sulphate aerosols from human-caused emissions have typical lifetimes of one to a few weeks, and they are localized around their source regions. Ironically, future clean-up of air pollution around major industrial regions will likely reduce the cooling effects of aerosols and result in a faster rate of climate warming.

2 Prentice, I.C., et al. 2001. The carbon cycle and atmospheric carbon dioxide. In J. T. Houghton et al. (eds.), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: pp. 183-238.

3 Folland, C.K. et al. 2001. Observed climate variability and change. In J. T. Houghton et al. (eds.), Climate Change 2001: The Scientific Basis. Contri bution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: pp 99-182.

4 Prentice et al. 2001

5 Prather, M., D. Ehhalt, and others. 2001. Atmospheric chemistry and greenhouse gases. In J. T. Houghton et al. (eds.), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: pp. 239-288.

6 Such projections are made after considering a range of possible future human development scenarios and resultant greenhouse gas concentrations, and feeding those greenhouse gas concentrations into global climate models. Climate models apply the laws of physics to the atmosphere, ocean, and land surface. They have been demonstrated to simulate 20th century climate quite well, including the observed trends in temperature. Cubasch, U. et al. 2001. Projections of Future Climate Change. In J. T. Houghton et al. (eds.), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: pp 525-582.

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19 As indicated by the midpoint of water year flow, that is, the date at which half the flow between 10/1 and 9/30 has occurred. In snowmelt-dominated basins this occurs much later than the midpoint of precipitation; for the mean inflow to Puget Sound, the midpoint typically occurs in March.

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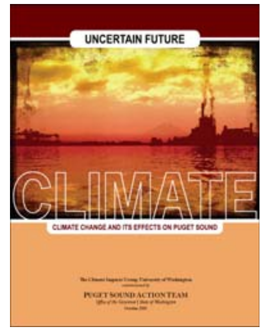
Uncertain Future: Climate Change and Its Effects on Puget Sound



Errata: Overview Document
February 13, 2007

The Climate Impacts Group has issued the following minor corrections to the report *Uncertain Future: Climate Change and Its Effects on Puget Sound*

- Figure 3, Average daily freshwater flow into Puget Sound (p. 17): The time interval used to construct the orange curve in Figure 3 was 1948-1967. Please also note this figure is incorrectly numbered as a second Figure 3.

- Figure 4, Simulated average runoff for the Puget Sound basin (p. 17): The warming used in the hydrologic simulation of future climate for Figure 4 was +2.3°C (4.1°F).

- Figure 6, Future sea level rise scenarios for various locations in Puget Sound (p. 21):

    - The endnote reference for Figure 6 (p.21) should be 81, i.e., Canning 1991.
    - The sea level rise curves slightly overpredict the highest rates of rise and slightly underpredict the lowest rates of rise. The correct sea level rise amounts for 2100 from this analysis are Tacoma 0.94 m, Seattle 0.83 m, Friday Harbor 0.68 m, and Neah Bay 0.41 m.

Additionally, the reader should note the following point of clarification about the Pacific Northwest warming trends shown in Figure 3 on page 14:

- The trend shown in Figure 3 shows changes in average temperature relative to the decade of the 1990s while the projected warming stated in the text on p.14 is relative to 1970-1999 average temperature. For the trend line in the figure to match the numbers provided in the text, the lines in the figure would be bumped up by 0.21°C (0.38°F).