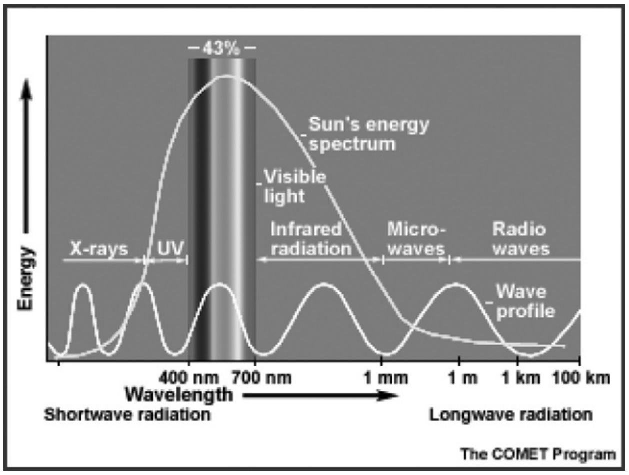
Solar Radiation

The sun radiates vast quantities of energy into space, across a wide spectrum of wavelengths.

Most of the radiant energy from the sun is concentrated in the visible and near-visible parts of the spectrum. The narrow band of visible light, between 400 and 700 nanometers (nm), represents 43% of the total radiant energy emitted. Wavelengths shorter than the visible account for 7 to 8% of the total, but are extremely important because of their high energy per photon. The shorter the wavelength of light, the more energy it contains. Thus, ultraviolet light, also called UV, is very energetic (capable of breaking apart stable biological molecules and causing sunburn and skin cancers). The remaining 49 - 50% of the radiant energy is spread over the wavelengths longer than those of visible light. These lie in the near infrared range from 700 to 1000 nm; the thermal infrared, between 5000 and 20,000 nanometers; and the far infrared regions. Various components of Earth's atmosphere absorb ultraviolet and infrared solar radiation before it penetrates to the surface, but the atmosphere is quite transparent to visible light.

Absorbed by land, oceans, and vegetation at the surface, the visible light is either transformed into heat and re-radiates in the form of invisible infrared radiation, or the energy is used to create vegetative matter through photosynthesis. If that was all there was to the story, then during the day Earth would heat up, but at night, all the accumulated energy would radiate back into space and the planet's surface temperature would fall far below zero very rapidly. The reason this doesn't happen is that earth's atmosphere contains molecules that absorb the heat and re-radiate the heat in all directions. These molecules are called 'greenhouse gases' because they serve to hold heat in like the glass walls of a greenhouse. Greenhouse gases are responsible for the fact that the Earth enjoys temperatures suitable for our active and complex biosphere.

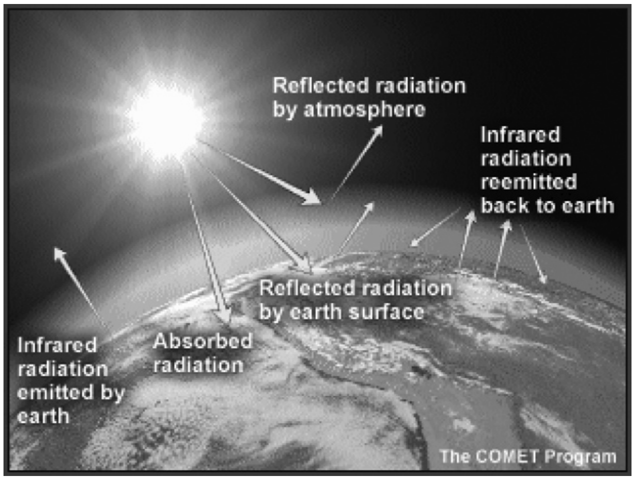
Atmospheric scientists (scientists who study the gaseous envelope surrounding the Earth) first used the term 'greenhouse effect' in the early 1800s.
At that time, it was used to describe the naturally occurring functions of trace gases in the atmosphere and did not have any negative connotations. It was not until the mid-1950s that the term greenhouse effect was coupled with concern about changes in the global climate. And in recent decades, we often hear about the greenhouse effect in somewhat

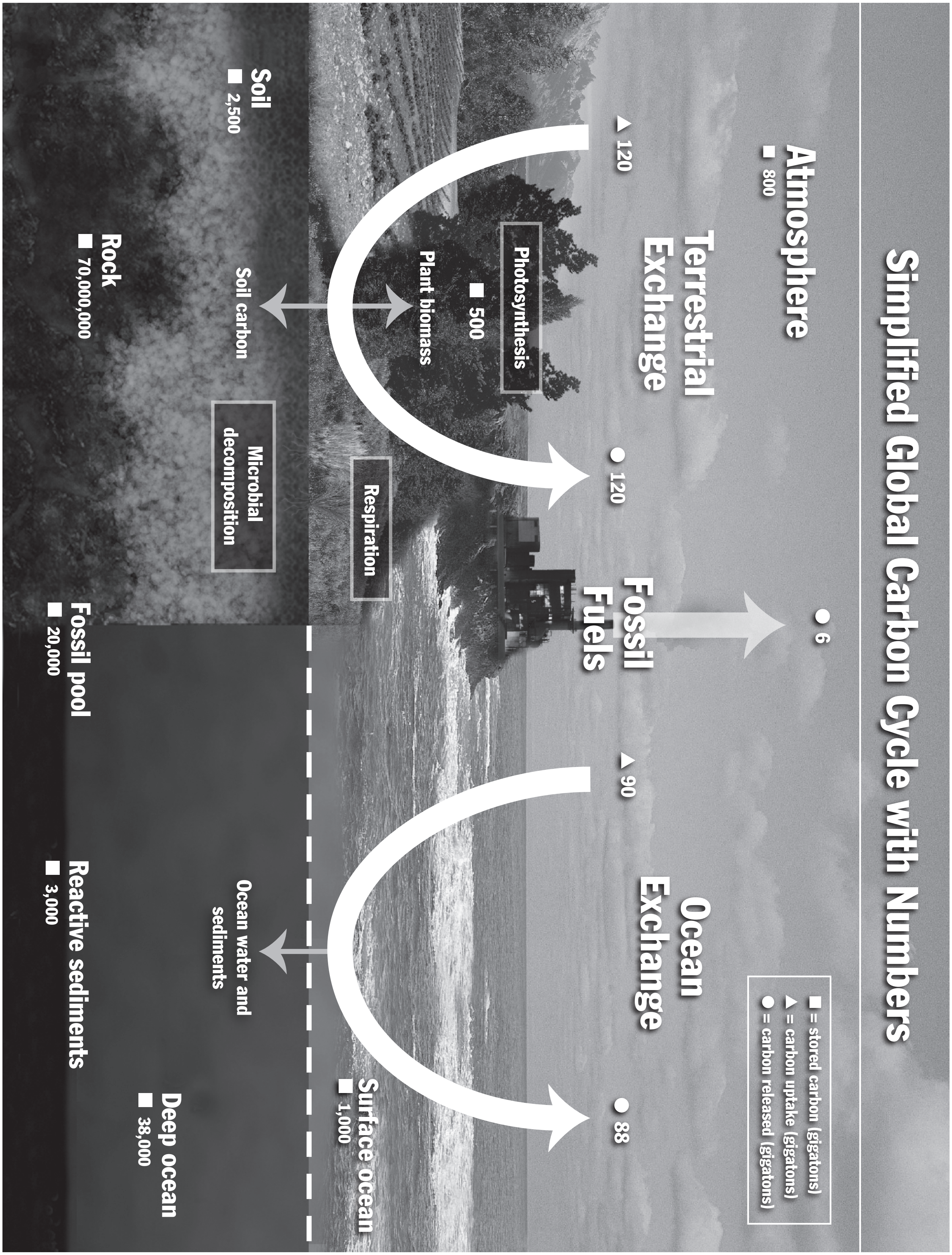


negative terms. The negative concerns are related to the possible impacts of an enhanced greenhouse effect. The enhanced greenhouse effect is sometimes called Global Warming. Global Warming refers to the gradual increase of the Earth's average surface temperature due to a build-up of greenhouse gases in the atmosphere. It is important to remember that without the greenhouse effect life on Earth, as we know it, would not be possible.

The term Greenhouse Effect comes from the idea that greenhouse gases produce an effect similar to the glass walls of a greenhouse. Both greenhouse gases around the Earth and the glass walls of a greenhouse allow solar radiation to enter a space and hold the heat generated by the solar radiation.

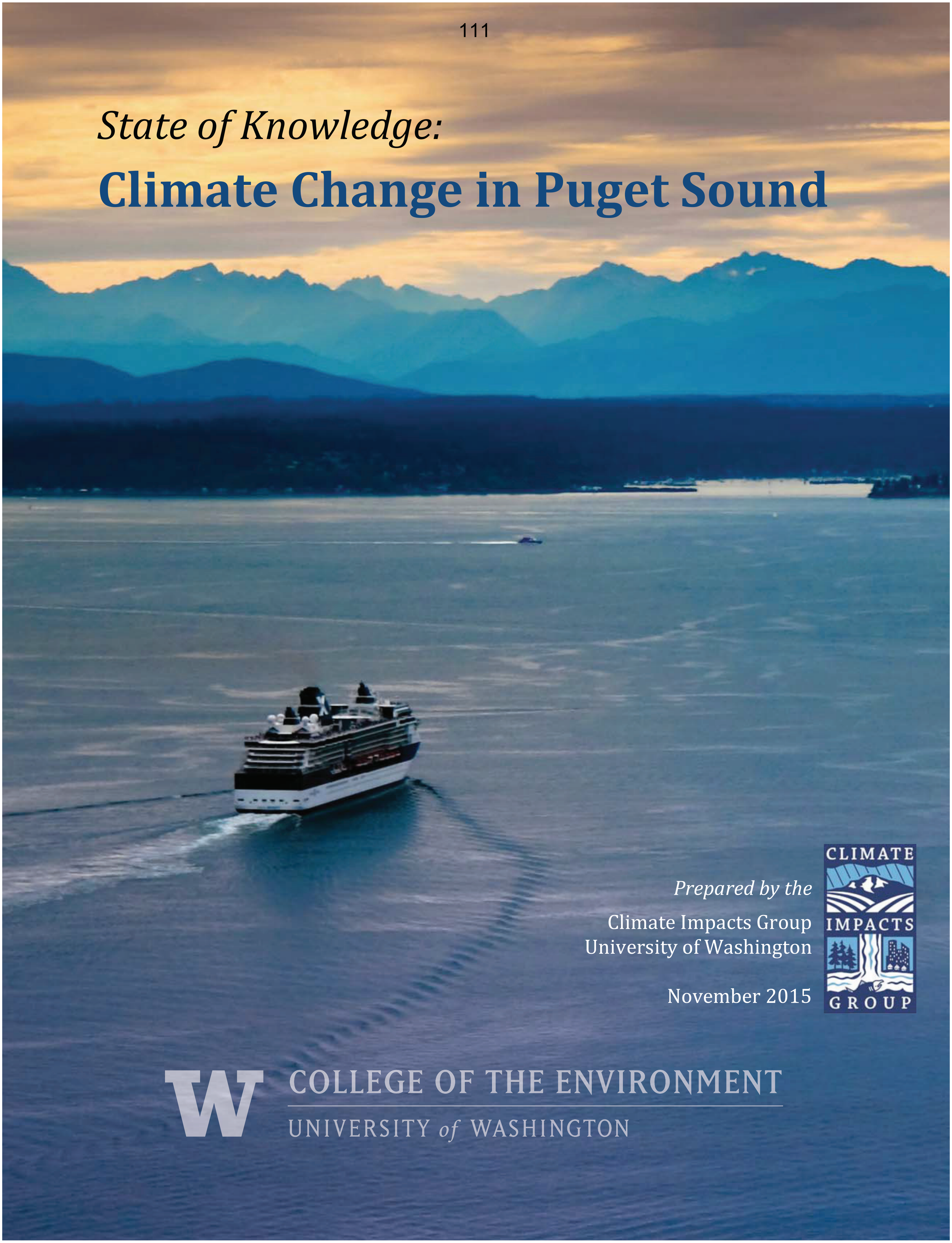
The source of this material is Project Learn at http://www.ucar.edu/learn from the University Corporation for Atmospheric Research (UCAR).




Simplified Global Carbon Cycle with Numbers
■ = stored carbon (gigatons)
▲ = carbon uptake (gigatons)
● = carbon released (gigatons)
Atmosphere
■ 800
Terrestrial Exchange
▲ 120
● 120
Photosynthesis
■ 500
Plant biomass
Soil carbon
Respiration
Microbial decomposition
Soil
■ 2,500
Rock
■ 70,000,000
Fossil Fuels
● 6
Fossil pool
■ 20,000
Ocean Exchange
▲ 90
● 88
Ocean water and sediments
Surface ocean
■ 1,000
Deep ocean
■ 38,000
Reactive sediments
■ 3,000

State of Knowledge:

Climate Change in Puget Sound



Prepared by the

Climate Impacts Group
University of Washington

November 2015

COLLEGE OF THE ENVIRONMENT
UNIVERSITY *of* WASHINGTON

Table of Contents

How to Read this Report

This report is designed to serve as a reference for individuals interested in understanding the state of the science on climate change and its effects within the Puget Sound region. We define the Puget Sound region to include the water bodies of Puget Sound and the Strait of Juan de Fuca, as well as any United States land areas that ultimately drain into these waters, as outlined in the map below.

Written so that the reader can choose a level of specificity that is appropriate to her/his needs, research findings are summarized within 13 sections, each focusing on a specific topic area. Each section provides a synthesis of the peer-reviewed literature on climate-related changes in Puget Sound. Some sections also include references to the gray literature (reports, PhD theses, and other previous syntheses) and a few include the results of unpublished data analyses. For transparency, the source of all data and statements is provided in the text. Although the sections refer to one another when necessary, each is written to serve as a stand-alone reference for that topic. Summary tables in Sections 2 through 4 provide a terse listing of the raw numbers associated with the findings listed within the text.

In most sections, the first sub-topic is entitled *"Climate Drivers of Change"*, which provides a summary of the mechanisms by which climate could effect change. Similarly, most sections include a final sub-topic entitled *"Climate Risk Reduction Efforts"*, which details recent and ongoing efforts by communities, agencies, tribes, and organizations that are working to prepare for the effects of climate change. Since the sections cover a wide range of sectors and impacts, some of which have been studied more thoroughly than others, not all of the same elements are included in each section.

The Puget Sound region, as defined in this report.
Figure Source: Robert Norheim.

The Soul of the Sound

Between upthrust cragged ranges, glacial carvings of
rugged beauty with great mountain peaks,
templed forests and crests of snow-

To Pacific Ocean beaches and coastal waters,
pulses Puget Sound and environs we strive to know!

Her dynamic hydro-keyboard is powered by ocean tides,
melted snow, river runoff, winds, and rain

And with her temperature, currents, salinity, density and
depth, develops a rhythmic gain

The Aleutian Low is the conductor
on the Sound's Pacific latitude,

And directs a fugue in bass clef pitch as it
compresses or extends its longitude!

This energy signals southerly winds,
laden with tropical moisture,

To the Sound or to Alaska in obeyance
to pressuring posture!

– Excerpted, with permission, from Ebbesmeyer et al. 1989[1]

[1] Ebbesmeyer, C. C., Coomes, C. A., Cannon, G. A., & Bretschneider, D. E. (1989). Linkage of ocean and fjord dynamics at decadal period. *Aspects of Climate Variability in the Pacific and the Western Americas*, 399-417. http://dx.doi.org/10.1029/GM055p0399

EXECUTIVE SUMMARY

From the peaks of the Cascades and Olympics to the saltwater of the Sound, climate shapes the physical landscape of the Puget Sound region and where and how people, plants and animals inhabit that landscape.

In addition to important natural variations, we know now that the Earth's climate is changing, and expected to continue to change in ways that will alter our local environment, the nature and health of our ecosystems, and the risks and opportunities facing our communities.

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems...*

This report summarizes the current state of knowledge concerning observed and likely future climate trends and their effects on the lands, waters, and people of the Puget Sound region. It describes:

- Changes in the key factors shaping our local environment: temperature, precipitation, sea level, ocean chemistry, and natural variability,
- Implications for Puget Sound lands: freshwater resources, landslides, sediment transport, agriculture, and ecosystems,
- Consequences for Puget Sound's marine waters: coastal and marine ecosystems, water quality, and circulation,
- Impacts on the region's population: health, tribes, and infrastructure, and
- Climate risk reduction activities underway in climate-sensitive sectors across the Puget Sound region.

> *...Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen."*
>
> *– IPCC Synthesis Report, Summary for Policy Makers, 2013*[1]

This report, State of Knowledge: *Climate Change in Puget Sound,* is designed to be an easy-to-read summary that both complements and points to the foundational literature (peer-reviewed science, community and agency reports, and publicly available datasets) from which it draws.

REPORT HIGHLIGHTS

Key Drivers of Change

Climate variability and change will affect the Puget Sound region by altering key climate-related factors shaping the local environment.

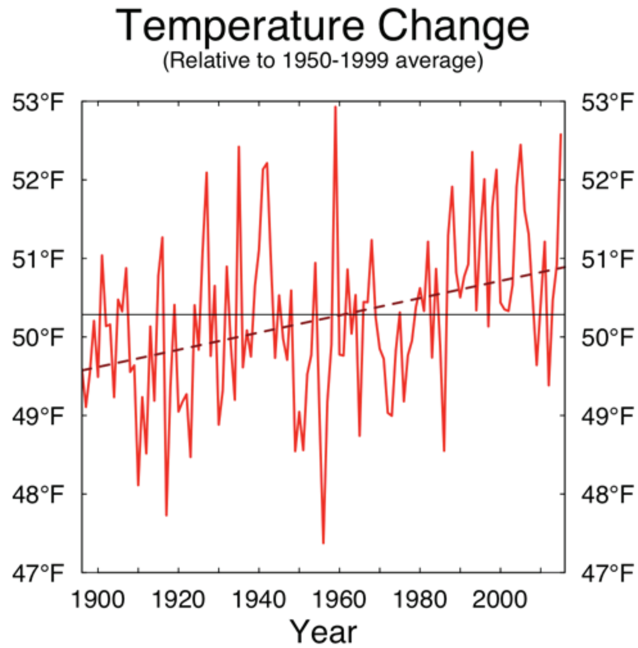


Figure ES-1. The Puget Sound region warmed by +1.3°F from 1895 to 2014. The red line shows average annual temperature for the Puget Sound Lowlands climate division,[A] the horizontal black line corresponds to the average temperature for 1950–1999 (50.3°F), and the dashed red line is the estimated trend. *Data source: Vose et al. 2014.*[A]

- **TEMPERATURE:** The Puget Sound region warmed in the 20th century: all but six of the years from 1980-2014 were above the 20th century average (Figure ES-1). Additional warming for the 21st century is projected to be at least double that experienced in the 20th century, and could be nearly ten times as large (Figure ES-2). *(Section 2)*

- **PRECIPITATION:** There are no statistically significant trends towards wetter or drier conditions (evaluated for seasons and years) over the 20th century**.** Large year-to-year and decade-to-decade variations in precipitation are expected to continue, and to be much larger than the long-term changes projected for the 21st century. *(Section 2)*

- **HEAVY RAINFALL:** Future occurrences of heavy rainfall are projected to be more frequent and more intense. This will exacerbate flood risks in many watersheds**.** *(Section 2)*

- **SEA LEVEL:** Over the last century, sea level rose at many locations along the shorelines of Puget Sound. Rates vary**,** however, as local land motion, weather patterns, and ocean currents can amplify or mask regional trends in sea level. Sea levels are projected to rise over the coming century, with a wide range of possible future amounts, depending on the rate of global greenhouse gas emissions. Increases in sea level will amplify the risk of coastal flooding. *(Section 4)*

- **OCEAN ACIDIFICATION:** As a result of accumulating carbon dioxide (CO_2) in the atmosphere, the waters of the North Pacific Ocean and Puget Sound are experiencing a reduction in pH, a process known as acidification. This acidification is projected to continue. *(Sections 7 and 11)*

- **NATURAL VARIABILITY:** Seasonal, year-to-year, and decade-to-decade variations will remain an important feature of local climate, at times amplifying or counteracting the long-term trends caused by rising greenhouse gas emissions.

Puget Sound Land Areas

From the mountaintops to the shorelines of Puget Sound, these climate changes will cause changes in the region's water cycle, natural resources, and ecosystems.

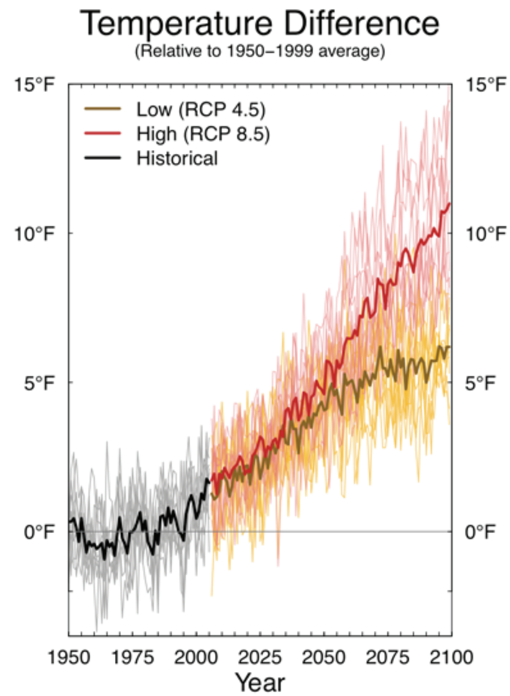


Figure ES-2. The Puget Sound region is projected to warm considerably in the 21st century. The graph shows average annual air temperatures projected by climate models, relative to the average for 1950-1999 (horizontal gray line; the average annual temperature for the Puget Sound region is 44°F). Thin colored lines show individual climate model projections; thick colored lines show the averages of the models. *Data source: Downscaled climate projections developed by Abatzoglou and Brown 2011.*[A]

- **SNOWPACK AND STREAMFLOW:** Warming will cause a greater proportion of winter precipitation to fall as rain rather than snow. Snowpack is projected to decline, causing the spring peak in streamflow to occur earlier in the year. Winter streamflow is projected to increase in snow-influenced watersheds, while most locations are projected to experience a decline in summer streamflow (Figure ES-3). *(Section 3)*

- **LANDSLIDES AND SEDIMENT TRANSPORT:** Changes in rainfall, snowpack, and streamflow may lead to an increase in landslide risk, erosion, and sediment transport in fall, winter, and spring, while reducing the rates of these processes in summer. Quantitative projections of the likely changes in sediment transport and landslides are limited, in part because it is challenging to distinguish climate change effects from non-climatic factors such as development patterns and forest management. *(Section 5)*

- **FLOODING:** Both the extent and the frequency of flooding is projected to increase. Heavy rain events are projected to intensify, increasing flood risk in all Puget Sound watersheds. Continued sea level rise will extend the reach of storm surge, putting coastal areas at greater risk of inundation. In snow-accumulating watersheds, winter flood risk will increase as the snowline recedes, shifting precipitation from rain to snow. *(Sections 2, 3, 4, and 5).*

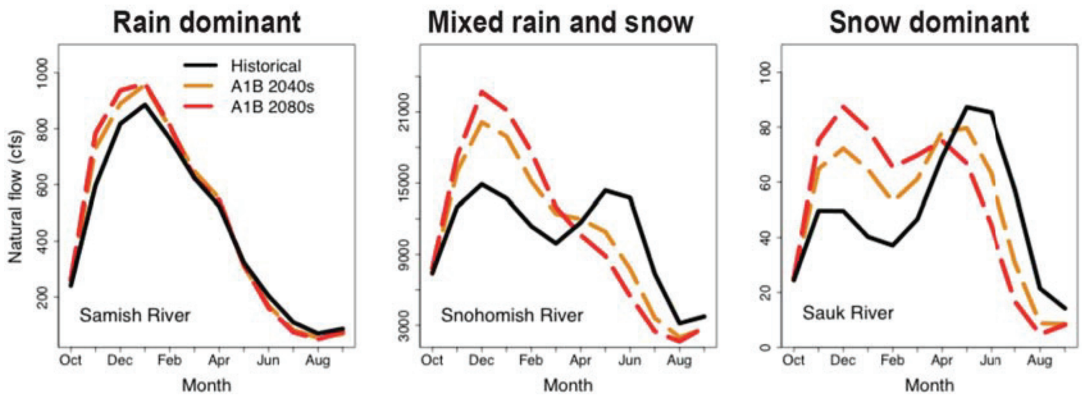


Figure ES-3. Streamflow is projected to increase in winter and decrease in summer, and changes are greatest for watersheds located near the current snowline. Changes in the seasonal timing of streamflow, on average, for three illustrative watersheds in Puget Sound: The Samish River, a warm basin (left); the Sauk River, a cold basin with source waters at high elevations (right); and the Snohomish River, a middle-elevation basin with substantial area near the current snowline (middle). *Data source: Downscaled hydrologic projections developed by Hamlet et al. 2013*[3]

- **SALMON:** Warmer streams, ocean acidification, lower summer streamflows, and higher winter streamflows are projected to negatively affect salmon. The persistence of cold water "refugia" within rivers and the diversity among salmon populations will be critical in helping salmon populations adapt to future climate conditions. *(Sections 10 and 11)*

- **TIMING OF BIOLOGICAL EVENTS:** The timing of many biological events (e.g., leaf emergence in spring, plankton blooms in lakes, spawning runs for salmon) can be altered by warming. Because each species will respond differently, climate change may cause important biological interactions to become unsynchronized. *(Sections 9, 10, and 11)*

- **SPECIES DISTRIBUTIONS:** Many species will exhibit changes in their geographic ranges, with some species experiencing expansion, while others experience contraction or migration. For example, declining snowpack is expected to lead to a decline in montane meadows as forests to expand into higher elevation habitats. Range shifts will vary among species, and will be affected by non-climatic factors such as development and management patterns. *(Sections 9 and 10)*

- **FORESTS:** Over the long-term, climate change is expected to alter the distribution and abundance of some tree species in the Puget Sound region. Growth of Douglas-fir and other species in relatively warm lower-elevation forests (where growth is currently limited by summer water availability) may decrease. In contrast, growth of cold-climate, high-elevation species such as mountain hemlock (where growth is currently limited by mountain snowpack) may increase. Increases in the risk of large wildfires and altered ranges and timing of insects and fungal pathogens will affect the vigor, growth, and distribution of forest species in the Puget Sound region. *(Section 9)*

- **AGRICULTURE:** Warming is expected to increase the length of the growing season. Along with higher temperatures, increases in atmospheric CO_2 concentrations could increase the production of some crops. However, increases in heat stress, decreases in summer water availability, increases in flood risk, and changes in the range and timing of pests may negatively affect crops and livestock. *(Section 8)*

Box ES-1. Projected changes in several key physical drivers.

- **Average annual temperature:** By the 2050s (2040-2069), the average year in the Puget Sound region is projected to be +4.2°F (range: +2.9 to +5.4°F) warmer under a low greenhouse gas scenario and +5.5°F (range: +4.3 to +7.1°F) warmer under a high greenhouse gas scenario (RCP 4.5 and 8.5, respectively),[A] relative to 1970-1999.[B,4]

- **Heavy Rainfall:** By the 2080s (2070-2099), the wettest days (99th percentile or 24-hour precipitation totals) in the Pacific Northwest are projected to increase by +22% (range: +5% to +34%) for a high greenhouse gas scenario (RCP 8.5), relative to 1970-1999.[C,5]

- **Declining Spring Snowpack:** By the 2040s (2030-2059), the average year in the Puget Sound region is projected to have −23% (range: −34 to −6%) less April 1st snowpack under a low greenhouse gas scenario (B1), and −29% (range: −47 to −4%) under a moderate greenhouse gas scenario (A1B), relative to 1970-1999.[C,3]

- **Sea Level Rise:** By 2050, relative sea level in Seattle is projected to rise by +6.5 inches (range: -1 to +19 inches) for a moderate, low, and high greenhouse gas scenario (A1B, B1 ,and A1FI, respectively), compared to 2000.[6] Sea level rise at other locations may differ by up to 8 inches by 2050, due to different rates of uplift or subsidence.

- **Higher Storm Surge Reach.** Although storm surge is not projected to increase, sea level rise will cause the same events to have a greater impact. In Olympia, a +6 inch rise in sea level (the middle projection for 2050 is +9 inches) would cause the 100-year surge event to become a 1-in-18 year event.[7]

A Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for details.

Puget Sound's Marine Waters

Climate change will affect the saltwater habitats of Puget Sound, driving changes in its currents, chemistry, and ecosystems.

- **COASTAL HABITATS:** Sea level rise is projected to expand the area of some tidal wetlands in Puget Sound but reduce the area of others, as water depths increase and new areas become submerged. For example, the area covered by salt marsh is projected to increase, while tidal freshwater marsh area is projected to decrease. Rising seas will also accelerate the eroding effect of waves and surge, causing unprotected beaches and bluffs to recede more rapidly. *(Sections 4 and 5)*

- **HARMFUL ALGAL BLOOMS:** Warmer water temperatures, both in the North Pacific Ocean and in Puget Sound, will likely make harmful algae blooms more frequent and severe, and will extend the season when they can occur. Ocean acidification may increase the toxicity of some harmful algal blooms. *(Sections 7 and 11)*

- **MARINE ECOSYSTEMS**: A combination of climate-related stressors will affect marine organisms and habitats, including warmer water temperatures, loss of coastal habitat due to sea level rise, ocean acidification, and changes in water quality and freshwater inputs. Some species, like salmon and shellfish, are likely to be negatively affected by these changes; other species, such as eelgrass, may benefit. *(Section 11)*

- **CIRCULATION IN THE OCEAN AND IN PUGET SOUND:** Future changes in the circulation of Puget Sound and the near-shore Pacific Ocean are unclear. Changes in the timing and amount of river flows may affect the ability of Puget Sound's surface and deep waters to mix. Ocean upwelling may change, but projections are not conclusive. Short-term variability in upwelling (ranging from seasons to decades) will likely be more important than long-term changes related to global warming throughout the 21st century. *(Section 6)*

B Projected change for ten global climate models, for 2050-2069 relative to 1970-1999, based on a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.

C Projected change for ten global climate models, for 2040-2059 relative to 1970-1999, based on a moderate (A1B) greenhouse gas scenario.

D The study evaluated precipitation totals on days with the top 1% (99th percentile) in daily water vapor transport, the principal driver of heavy rain events in the Pacific Northwest. Projections are based on an analysis of 5 global climate model projections and a high greenhouse gas scenario (RCP 8.5), evaluated for 2070-2099 relative to 1970-1999. Projected changes in intensity were evaluated for latitudes ranging from 40 to 49N. Although global models are coarse in spatial scale, previous research has shown that they can adequately capture the dynamics that govern West coast storms and heavy precipitation events.

E Projections are a particular class of global climate models called "Earth System Models". These model the carbon cycle, and can therefore provide estimates of the amount of CO_2. The numbers give the range among all models and two scenarios: both a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.

People

The Puget Sound region is home to a growing population and a rich diversity of cultural, institutional, and economic resources, many of which will be affected by climate change.

> *"Whether the consequences of the climate impacts…are severe or mild depends in part on the degree to which regional social, economic, and infrastructural systems are adjusted to align with the changing climate, and the degree to which natural systems are provided with the room, flexibility, and capacity to respond. The regional consequences of climate change will also be strongly shaped by past choices—of what to build where, what to grow where—and by the laws, institutions, and procedures that shape how natural resources are managed and allocated, risks from natural hazards are identified, and trade-offs among conflicting objectives resolved." – Snover et al., 2013*[2]

- **TRIBES:** Rooted in place, tribes are particularly vulnerable to climate change. Puget Sound's tribal communities face a wide range of climate-related risks, including sea level rise, more frequent and larger floods, impacts on culturally-important species such as salmon and shellfish, a greater risk of wildfires, and changes in the forest, coastal, and marine ecosystems on which they rely.

- **BUILT ENVIRONMENT:** The developed areas of Puget Sound and the transportation, drinking water, wastewater, and energy systems that serve the region's population will face an increasing risk of a variety of extreme weather events (e.g., heat waves, flooding, wildfire). Consequences include flooding of low-lying infrastructure, damage to energy transmission, and higher maintenance costs for many transportation and other elements of the built environment. *(Section 12)*

- **HUMAN HEALTH:** More frequent heat waves and more frequent and intense flooding may harm human health directly. Warming may also exacerbate health risks from poor air quality and allergens. Climate change can indirectly affect human health through its impacts on water supplies, wildfire risk, and the ways in which diseases are spread. Risks are often greatest for the elderly, children, those with existing chronic health conditions, individuals with greater exposure to outside conditions, and those with limited access to health resources. *(Section 13)*

Climate Risk Reduction

Actions taken today to reduce climate risks will play an important role in determining the future consequences of climate change. Actions underway in Puget Sound include:

- **ASSESSING VULNERABILITIES:** Many Puget Sound communities and organizations are assessing their specific vulnerabilities to climate change. For example, the Jamestown

S'Klallam tribe has recently completed a vulnerability assessment, finding that scenarios for moderate and high severity sea level rise raise flood risks for Highway 101 near Discovery Bay, potentially preventing the Tribe's access to the highway for 12-24 hours.[8] *(Section 12)*

- **PARTNERSHIP BUILDING:** Agencies, organizations, and communities in Puget Sound are working collaboratively with stakeholders to identify options for responding to climate change. For example, the North Cascadia Adaptation Partnership is a U.S. Forest Service / National Park Service collaboration that joined with city, state, tribal, and federal partners to increase awareness of climate change, assess the vulnerability of cultural and natural resources, and incorporate climate change adaptation into current management of federal lands in the North Cascades region.[9] *(Section 9)*

- **CLIMATE-INFORMED PLANNING:** Puget Sound communities and practitioners are incorporating climate change impacts into planning and decisions. For example, plans by the Port of Bellingham to redevelop the 228 acre Georgia Pacific site near downtown Bellingham include raising site grades approximately +3 to +6 feet in areas with high value infrastructure as a buffer against sea level rise.[10] *(Sections 4 and 12)*

- **IMPLEMENTING ADAPTATION:** A number of Puget Sound communities have begun to implement changes in policies, practices, and infrastructure that are designed to increase climate resilience. For example, projections for increased flooding and sediment loading in the Skagit River led to design changes for the City of Anacortes' new $65 million water treatment plant. Completed in 2013, the new plant includes elevated structures, water-tight construction with minimal structural penetrations, no electrical control equipment below the current 100-year flood elevation, and more effective sediment removal processes.[11,12] *(Sections 3, 5, and 12)*

Looking Forward

Understanding the likely local effects of climate variability and change is the first step towards characterizing, and ultimately reducing, climate risks. To help catalyze and support climate risk reduction activities aimed at developing a climate resilient Puget Sound region, this report summarizes existing knowledge about observed climate change and variability in the Puget Sound region, likely future climate changes, and the current and possible future impacts associated with these changes. It is intended to serve as a credible source to inform discussions within the region about the risks associated with climate change and choices for adaptation.

It is important to recognize that this report does not serve as a crystal ball for predicting our future. The actual impacts of a changing climate will arise from the complex interactions between climate and our critical natural and human systems, but also with a multitude of non-climate factors, including development choices, patterns of energy and water consumption, land use decisions, and other economic and social factors.

The region's best future will be achieved if the early steps toward climate risk reduction can be connected and enhanced. Decisions that consider climate risks, the interactions among these risks, and the connection between these risks and non-climate stressors offer the opportunity to maintain the integrity of the ecosystems that we treasure, the reliability of the infrastructure on which we depend, and the well-being of this generation and future generations in the Puget Sound region.

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11 City of Anacortes. 2012. "*City of Anacortes, Water Treatment Plant, Climate Change Impact Mitigation.*" Presentation to Washington State Senate Environment Committee by City of Anacortes Public Works, Committee Working Session, November 30.

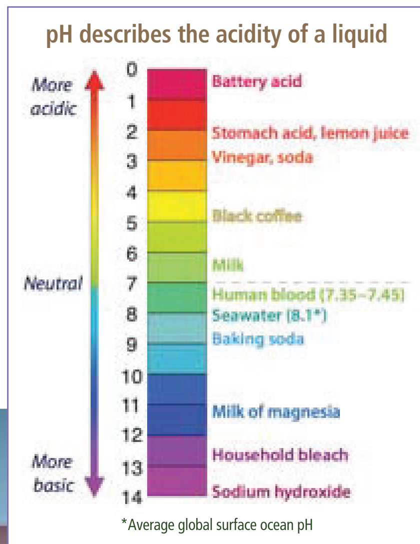
12 Reeder, W.S. et al., 2013. Coasts: Complex changes affecting the Northwest's diverse shorelines. Chapter 4 in M.M. Dalton, P.W. Mote, and A.K. Snover (eds.) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*, Washington D.C.: Island Press.

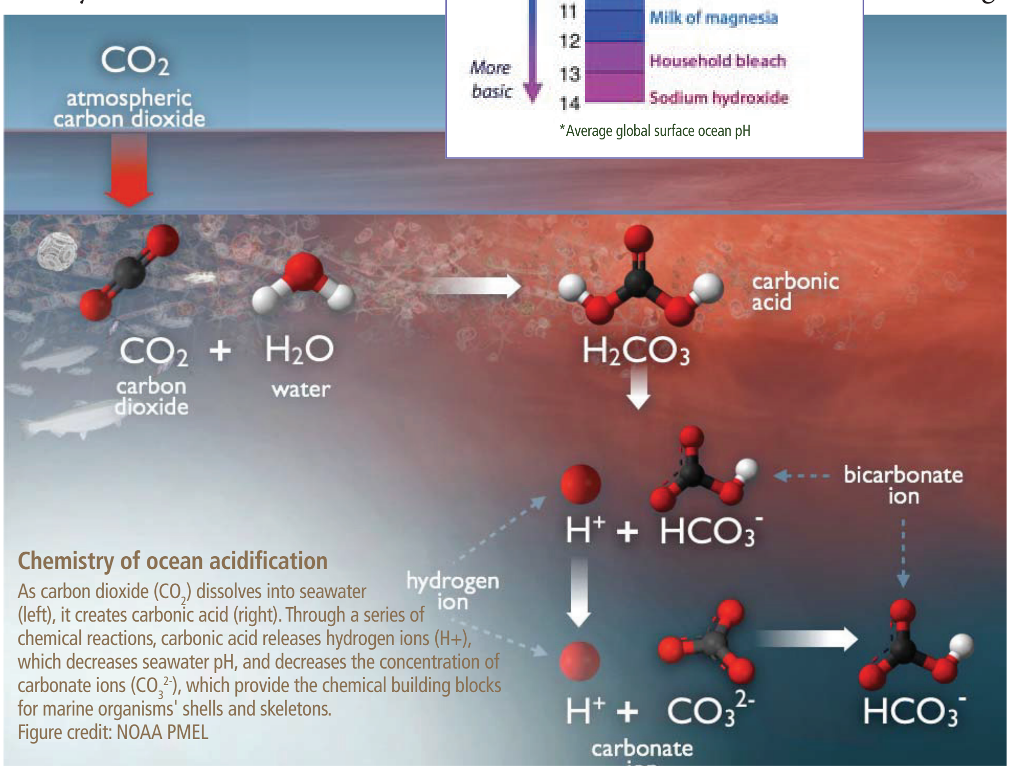
University of Washington • Washington Sea Grant

Ocean Acidification in Washington State

What is Ocean Acidification?

Ocean Acidification (or 'OA') is a long-term decrease in seawater pH that is primarily caused by the ocean's uptake of carbon dioxide (CO_2) from the atmosphere. CO_2 generated by humans' use of fossil fuels and deforestation has been accumulating in the atmosphere since the industrial revolution. About one quarter of this CO_2 is absorbed by the oceans, where it reacts with water to form carbonic acid. As a result, the average pH of seawater at the ocean surface has already dropped by ~0.1 units, a 30% increase in acidity. If atmospheric CO_2 levels continue to climb at the present rate, ocean acidity will double by the end of this century.





Chemistry of ocean acidification
As carbon dioxide (CO_2) dissolves into seawater (left), it creates carbonic acid (right). Through a series of chemical reactions, carbonic acid releases hydrogen ions (H+), which decreases seawater pH, and decreases the concentration of carbonate ions (CO_3^{2-}), which provide the chemical building blocks for marine organisms' shells and skeletons.
Figure credit: NOAA PMEL

OA in Washington State

Our region is experiencing ocean acidification sooner and more severely than expected, due to a combination of human and natural causes. In the spring and summer, acidification along our coast is compounded by upwelling, which mixes deep, naturally low-pH seawater into the already acidified surface layer. In Puget Sound, nutrients generated by human activities (mostly nitrogen and phosphorus from sewage, fertilizers and manure) fuel processes that add even more CO_2 to this 'doubly-acidified' seawater. The combination can be deadly to vulnerable organisms. pH levels as low as 7.4 have been recorded in Hood Canal, an important shellfish-growing region. State and federal agencies, scientists, tribes, shellfish growers and NGOs are working together to address OA in our region.

What does OA mean for marine life?

As seawater becomes more acidic, *calcifiers* — marine organisms such as oysters, pteropods and corals — have to work harder to obtain the dissolved minerals they need to build their calcium carbonate shells and skeletons. This extra effort leaves them with less energy to spend on other important activities like growth and reproduction. Juveniles seem to be

over

especially vulnerable to acidification; shellfish hatcheries now monitor seawater chemistry carefully to avoid exposing their larvae to corrosive conditions that can kill them overnight. Even animals that don't have shells are feeling the effects of acidification. High levels of dissolved CO_2 cause a range of sensory, behavioral, and metabolic effects in fish and invertebrates.

What OA is not….

- Ocean acidification does *not* mean the oceans are becoming *acidic* (i.e. pH less than 7). The term "acidification" refers to a shift in pH towards the acidic end of the scale; similar to the way an increase in temperature from -20°C to 0°C (-4°F to 32°F) would be described as "warming," even though it's still cold.
- Seemingly small changes in pH are *not* insignificant. The pH scale, like the Richter scale, is logarithmic; that means pH 7 is *10 times* as acidic as pH 8. Because most animals and plants have a narrow pH "comfort zone," even a small increase in acidity can be very stressful.
- OA is *not* a future threat; it's already happening, and is having serious impacts on Washington State's marine resources and the people who depend upon them.
- OA is *not* just an "oyster problem." Oysters have been called "canaries in the coal mine" because it was oyster hatchery die-offs that first drew attention to the issue in the mid-2000's, but many other species have since shown signs of vulnerability as well. Unless we do something soon, the marine food web may change in dramatic and unpredictable ways as more and more species struggle to cope with changing seawater chemistry.

Learn more

Visit Washington Sea Grant's Ocean Acidification webpage for more information *wsg.washington.edu/our-northwest/ocean-acidification/*.

What can be done?

- In 2012, Washington Governor Christine Gregoire appointed a Blue Ribbon Panel on Ocean Acidification to assess the problem and recommend solutions. The state continues to work on ways to reduce CO_2 emissions, fund OA monitoring and research programs, and help the shellfish industry adapt to changing seawater chemistry.
- If protecting the Washington's marine environment and economy from the effects of OA is important to you, let your local and federal decisionmakers know! Ask them to support programs that will help us understand and address OA and its causes.
- Although OA is a global problem that will require global solutions, there *are* things you can do to mitigate OA locally. Reducing your carbon footprint, keeping nutrients out of the marine environment, and getting engaged in marine conservation will help make Washington's marine waters more resilient to OA. Check out Washington Sea Grant's OA Action Page for tips *wsg.washington.edu/our-northwest/ocean-acidification/what-can-you-do-about-oa/*.

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Sea Grant Washington

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

UNIVERSITY *of* WASHINGTON
COLLEGE OF THE ENVIRONMENT

Beyond Cutting Emissions

Protecting Wildlife and Ecosystems in a Warming World

DEFENDERS OF WILDLIFE

Introduction

Global warming, once the province of computer modelers and futurists, is upon us. Each year since 1993 has been among the top 20 warmest years on record, with 1998 and 2006 the hottest years ever for the United States.[1] A recent report by the Department of Agriculture concluded that global warming is already here and will continue to affect U.S. water resources, agriculture, land resources and biodiversity.[2] The Intergovernmental Panel on Climate Change (IPCC)—an organization that represents the international scientific consensus on climate change—predicts that by the end of the 21st century there will be global warming between 3 and 10 degrees Fahrenheit (F), possibly warmer than anytime in the past 450,000 years.[3]

Scientists warn that mid-range climate warming could cause 15 percent to 37 percent of the Earth's plants and animals to go extinct between now and 2050.[4] The composition and functioning of our natural ecosystems—and the vital life-supporting services they provide to people and wildlife alike—are changing and deteriorating with increasing speed.

If we do not take action now to address both the causes and effects of global warming from a social, ecological and economic point of view, the consequences will be enormous. Human communities and industries will lose the healthy ecosystems and the plants and animals that enhance our quality of life, produce valuable natural resources, help purify our air and water and perform other life-sustaining services.

Reducing emissions of the heat-trapping greenhouse gases—the primary cause of global warming—is not enough to protect our vulnerable natural systems. Because of the delayed climatic impact of greenhouse gas emissions, gases already in the atmosphere guarantee warming for many decades to come.[5] The United States also must act rapidly to lessen the impact of the global warming we have already set underway and make addressing the effects of global warming on ecosystems and wildlife a top national priority.

This report underscores the urgency of the situation by identifying specific threats global warming poses to our wildlife and ecosytems and the failures and weaknesses in the response of our government agencies so far. It also lays out a specific course of action that calls for a new conservation paradigm to guide resource managers in our warming world and a well-funded, coordinated, national response involving state, tribal and federal agencies.

Understanding the Threats to Wildlife and Ecosystems

ANALYSES OF HUNDREDS OF STUDIES REVEAL a disturbing truth: Global warming is already affecting a majority of U.S. species. One review found that more than 80 percent of plants and animals studied are shifting their ranges because of warming.[6] These species are responding to a global temperature rise of less than 1 degree F over the past 100 years and are likely to be put at risk by at least another 3 to 10 degrees of warming by 2100, if we do not take immediate and decisive action to reduce greenhouse gas emissions.[7]

Our clearest warning of the future lies in the Arctic, where warming has been more rapid than in the rest of the United States. Many areas of Alaska have already experienced rises of more than 5 degrees F and melting permafrost. Spruce and other trees are dying over many millions of acres, killed by spruce budworm and other pests previously controlled by colder temperatures. Even tundra is warming and drying to the point of burning: the largest-ever tundra fire on Alaska's North Slope—220,000 acres—was reported in 2007.[8]

The IPCC predicts global mean temperatures could rise well above 5 degrees F within this century.[9] If this happens, one-quarter of known species could become extinct and over one-fifth of the world's ecosystems could disappear.[10]

Global warming is already having an impact on the natural ecosystems that provide fundamental life-sustaining services without which human civilizations would cease to thrive. These "ecosystem services" include purifying air and water, forming fertile soils, pollinating crops, controlling insects, protecting coastal communities from storm surges and regulating the climate. Plants and animals also provide many direct goods to society, ranging from timber to food to new medicines. Nature and wildlife also offer significant recreational, aesthetic and emotional benefits.

The effects of global warming on the physical and biological elements of nature pose numerous threats to wildlife and the ecosystems that sustain and fulfill human life.

MELTING ICE AND SNOW

Researchers predict a 30-percent loss of Arctic sea ice by 2040,[11] possibly resulting in the disappearance of all polar bears from Alaska due to drowning, starvation, reproductive declines, dispersal and related effects.[12] Other species threatened by loss of Arctic sea ice include spectacled eider ducks, Ross and ivory gulls, ice-breeding seals, walruses and gray whales. The latter have been washing up emaciated since 2001, apparently because melting ice is decreasing their crustacean food supply.[13] The world-renowned Porcupine caribou herd, which calves in the Arctic National Wildlife Refuge, has declined more than 3 percent every year since 1989. Some scientists believe an important factor in the decline is the freezing rain—a result of climate change—that now ices over the caribou's winter food.[14]

DROUGHTS AND FOREST FIRES

In some areas, climate change will decrease rainfall, but even in areas where rainfall remains constant or increases, warming will increase evaporation rates, which can dry soils and make droughts more frequent. With rising temperature, the snow pack melts quickly so less water is available in late spring and early summer when wildlife, farmers and communities need it most. As forests die from rising temperatures and drought, their ability to store and gradually release water is impaired.

Water loss is expected to decrease freshwater fish habitat by 28 percent in the Rocky Mountains and reduce salmon habitat 18 percent nationwide.[15] One study projected that drought in the 64-million-acre prairie pothole region could reduce North America's annual duck production by up to 70 percent,[16] dealing a significant economic blow to the nation's hunting industry. In the Arctic, waterfowl breeding areas are projected to decrease by up to 50 percent within this century.[17]

Drought stress makes trees vulnerable to insect attack, and the combination of insect-killed trees, low moisture and high temperatures

More than 80 percent of plants and animals studied are shifting their ranges because of warming.

THE ECONOMIC BENEFITS OF PROTECTING WILDLIFE AND ECOSYSTEMS

Natural ecosystems provide goods, such as food and medicine, and life-support services essential to a civilization's ability to thrive. Society often greatly undervalues the services flowing from natural systems because many of them are performed "for free." These "ecosystem services" include purifying air and water, generating fertile soils, controlling pests that destroy crops, providing essential habitat for wildlife, sequestering carbon and controlling floods. As the examples below illustrate, protecting natural ecosystems and the wildlife that inhabit them from global warming and other threats is essential to sustaining human life and a vibrant economy with measurable benefits for individuals, businesses and communities.

Drinking Water: A conservative estimate for the value of water flowing from our national forests, where the headwaters of many rivers lie, is more than $4.3 billion annually.[18] The Catskill watershed provides New York City with much of its clean drinking water. Replacing the water filtration services provided by this watershed with a water treatment plant would cost $6 billion to $8 billion plus annual operating costs of $300 million.[19]

Medicine: Thirty percent of all pharmaceuticals on the market today were developed from natural compounds found in the wild.[20] Examples range from the commonplace (aspirin) to potent anticancer agents.[21]

Recreation: Fishing, hunting, wildlife watching, hiking and other outdoor pursuits that rely heavily on healthy wildlife populations, forests, rivers and ecosystems contribute $730 billion annually to the U.S. economy, support nearly 6.5 million jobs and generate $88 billion in state and national tax revenue.[22] One study of campsites in eastern Texas showed that recreation income is dropping dramatically as the southern pine beetle—a pest that has flourished with warmer winters and springs—kills increasing numbers of pine trees.[23]

U.S. coral reefs, significantly threatened by warming ocean temperatures and ocean acidification, are worth an estimated $30 billion per year in tourism, fish breeding habitat, shoreline protection and other services.[24] The Florida Keys National Marine Sanctuary alone supports almost 10,000 jobs in Monroe County, Florida.[25]

A fly fisher works Maroon Lake in Colorado's White River National Forest. Healthy wildlife populations and ecosystems are essential to the outdoor recreation industry, which pumps an estimated $730 billion a year into the U.S. economy.

Storm Surge Protection: Coastal marshes and mangroves are essential barriers for protecting coastal and inland communities from storm surges. A recent study estimates that these storm-protection services are worth more than $23 billion annually to U.S. cities and regions most vulnerable to hurricane and tropical storm surges.[26]

Agriculture and Forestry: More than 30 percent of our food crops rely on the services of pollinators,[27] and the value of the free pollination services provided by native insects is an estimated $3.1 billion per year. The estimated value of the pest control provided by insects and other wildlife is $4.5 billion per year.[28] The U.S. timber industry, already suffering from widespread insect attacks associated with warming, generates more than $125 billion annually, while supporting more than 500,000 jobs.[29]

resulted in a seven-fold increase in the amount of forested federal land that burned from 1987 to 2003 as compared to 1970 to 1987.[30] The largest number of acres ever burned to date was 8.6 million in 2005.[31] In the West, most climate models foresee significantly wetter winters with more fuel growth, leading to drier summers—the precise conditions conducive to massive wildfires that cause billions of dollars in property damage and destroy millions of acres of habitat.[32]

INCREASED RAINFALL AND FLOODING

Increased annual or seasonal precipitation expected in some areas will severely stress ecosystems currently adapted to drier conditions. For example, some researchers predict that increased precipitation and temperatures in the interior West may allow oak and other woody species to invade sagebrush lands, reducing them from millions of acres to isolated remnants.[33] Larger peaks in spring runoff due to faster snowmelt could cause floods that destroy streamside vegetation and fish spawning areas. More runoff can also be expected in areas where global warming impairs the ability of forests to store and gradually release water.

SEA-LEVEL RISE

Rising seas threaten coastal ecosystems and the communities and businesses that depend upon them. Storm surges from the larger and more frequent storms caused by global warming could inundate or wash over coastal wetlands that support critical seafood and recreation industries. One study of four coastal wetlands projected a mean loss of 44 percent of coastal bird habitat resulting from a 4.5-degree F global temperature rise.[34]

HABITAT AND RANGE SHIFTS

Some species will lose habitat altogether as their ranges shift or disappear due to climate change. Global warming is already resulting in significant range shifts among a wide variety of species. Ranges of reef fish in southern California have been shifting to the north since the 1970s.[35] Edith's checkerspot butterfly has shifted its range north by roughly 65 miles and upward 312 feet since the 1930s.[36] Many common birds such as the northern mockingbird and the common ground dove have also shifted their ranges north over the past 26 years.[37] The pika, a small, mountain-dwelling mammal, is moving farther upslope in search of a cooler environment, often to no avail.

DIRECT TEMPERATURE EFFECTS

Many studies have demonstrated that global warming is causing plants to flower earlier, insects to mature more quickly, and birds to migrate sooner.[38] For alligators, sea turtles and some other reptiles for which the number of male and female hatchlings is determined by egg incubation temperatures, some researchers fear global warming could skew sex ratios enough to prevent successful mating and lower reproductive success.[39] Corals are extremely susceptible to temperature increases—warming of even 2 degrees F above 1990 levels will bleach all coral reefs and warming of 3.6 degrees F would result in mass mortality of corals throughout the world.[40] Eastern brook trout, an iconic species that supports an important recreational fishing industry, dies when exposed for only a few hours to stream

temperatures of 76 degrees F or higher.[41] One study predicted that with an increase of 5.4 degrees F, up to 92 percent of the streams suitable for brook trout in North Carolina and Virginia would be lost.[42]

EXCESS CARBON DIOXIDE

High carbon dioxide levels—one of the major causes of warming—are changing the oceans' acidity. This is because the ocean absorbs much of the carbon dioxide in the atmosphere. The resulting increase in acidity reduces concentrations of calcium carbonate that coral animals need to build their limestone reefs. Some scientists believe that within the current century many corals will be unable to build reefs.[43]

INVASIVE SPECIES

Invasive species have played a role in the decline of 35 percent to 46 percent of the plants and animals on the U.S. endangered species list.[44] Unfortunately, most harmful invasive species in the United States are native to tropical and subtropical areas. These species will benefit from global warming at the expense of native plants and animals that prefer cooler temperatures.

According to a recent study, 48 percent of harmful invasive species

A herd of caribou stampedes through the Arctic National Wildlife Refuge. The Porcupine caribou herd has declined more than 3 percent every year since 1989, possibly due to climate-change-related freezing rain icing over lichens and other vital winter foods.

surveyed are likely to expand their ranges with rising temperature and only 4 percent are likely to contract their ranges.[45] Species likely to spread include the aggressive water-depleting shrub tamarisk,[46] the freeze-intolerant Chinese tallow tree and the disease-carrying Asian tiger mosquito.[47] The balsam wooly adelgid, a sap-sucking insect from Europe that reproduces more quickly under warmer conditions, has already destroyed 95 percent of Fraser firs in Great Smoky Mountains National Park.[48]

The cost of controlling fire ants, an invasive species that kills off native ants and preys on young bobwhite quail, least terns, gopher tortoises and other vertebrates, tops $1.2 billion per year in Texas alone.[49] After an explosive colonization in the southern United States, cold temperatures slowed the northward expansion of these ants,[50] but experts warn that global warming is likely to restart this harmful ant's march north.[51]

CHANGES IN ECOSYSTEM COMPOSITION

As the Earth warms, species will shift their geographic ranges. Birds might shift rapidly to the north, colonizing new areas, while slow movers like land snails and salamanders will seriously lag behind, possibly surviving only as remnant populations at higher elevations where temperatures remain cool. Such range shifts will shuffle species, creating new communities of plants and animals as most areas lose species and others gain new ones. Plants and animals will find themselves coping with new predators, diminished or different prey, and new competitors.[52] Many species—up to 25 percent, according to the IPCC—will be unable to survive these new conditions.

Migratory birds and other species that depend on different habitats at different times will face multiple threats if multiple habitats change. The red knot is an endangered sandpiper that flies more than 9,000 miles every spring from South America to the United States.[53] This migratory shorebird could lose up to 37 percent of its tundra breeding habitat to climate change by 2100—about the same time rising sea levels are expected to claim vital stopover habitat for knots and other migratory shorebirds in Delaware Bay.[54] The red knot's situation is not unique. One study projects that parts of the United States will lose 30 to 57 percent of their migratory bird species if temperatures rise 6.5 degrees F.[55]

Entire ecosystems may be lost when trees, corals or other foundation species that determine ecosystem structure dwindle or disappear. Eastern hemlock forests provide 2.3 million acres of dense forest habitat for species like deer and shade-loving brook trout.[56] The hemlock, the most long-lived tree in eastern North America, is under attack throughout the southern portion of its range from the hemlock wooly adelgid insect, a pest particularly lethal to drought-stressed trees.[57] Scientists fear that global warming will increase the range and severity of this insect, killing entire forests and affecting the species dependent on them.

IMPACTS TO ALREADY STRESSED SPECIES

Climate change will increasingly threaten the more than 1,300 species listed as threatened and endangered in the United States that are already vulnerable to human-caused stresses, such as habitat loss, fire suppression, pollutants and invasive species. Entire ecosystem types are in serious trouble even without climate change. Filling, dredging, dams and flood control have claimed 50 percent of wetlands in the continental United States and another 60,000 acres of wetlands vanish every year.[58] Midwest tallgrass prairies have vanished under the plow.[59] Suburban development in California has left only 15 percent of the coastal sage scrub ecosystem intact.[60] In the Southeast, habitat fragmentation, logging and fire suppression have reduced 90 million acres of longleaf pine ecosystem to scattered remnants and put its gopher tortoise, Eastern indigo snake and red-cockaded woodpecker on the endangered species list.[61]

Migratory birds and other species that depend on different habitats at different times will face multiple threats.

Because of habitat loss, many ecosystems and the plants and animals that inhabit them are isolated in tiny islands of habitat surrounded by cultivated land, highways and cities. When temperatures rise, species will try to follow their preferred climates north or upslope, but human development will completely block such movements and cause further risk of extinctions.[62]

Despite these many daunting threats, our federal, state and tribal agencies have yet to respond effectively to global warming. Before we can rise to the challenge of helping fish, wildlife and ecosystems reduce their vulnerability to climate change, we must recognize and overcome the weaknesses and failures of our response so far.