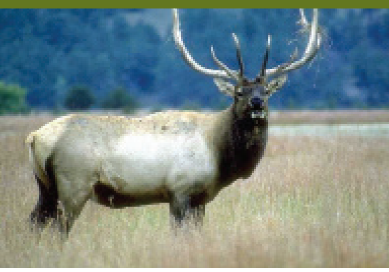
SCIENCE
in the service of
WASHINGTON STATE

WASHINGTON STATE Academy of Sciences




Climate Change in Washington State:

Research Questions Critical to Preparing for the Future




Summary of the Proceedings of the Tenth Annual Symposium
Held as Part of the 2017 Annual Meeting of the
Washington State Academy of Sciences
September 14, 2017, Museum of Flight, Seattle, WA

December 2017

PAGE LEFT
INTENTIONALLY BLANK

Climate Change in Washington State: Research Questions Critical to Preparing for the Future

Summary of the Proceedings

of the Tenth Annual Symposium held as part of the 2017 Annual Meeting of the Washington State Academy of Sciences

September 14, 2017
Museum of Flight, Seattle, WA

Proceedings Released
December 2017

Table of Contents

Board of Directors

President

Anjan Bose, Washington State University, Regents Professor, and the Distinguished Professor of Electric Power Engineering in the School of Electrical Engineering and Computer Science

President Elect

Ronald Thom, Pacific Northwest National Laboratory, Staff Scientist Emeritus - Coastal Sciences Division

Past President

Allan Konopka, Purdue University, Emeritus Professor of Biological Sciences

Treasurer

Cathryn Booth-LaForce, University of Washington, Professor - Family & Child Nursing, Adjunct Professor, Psychology

Secretary

Don Baer, Pacific Northwest National Laboratory, Laboratory Fellow - Environmental Molecular Sciences Laboratory

Board Members

Shirley Beresford, University of Washington, Senior Associate Dean - School of Public Health

Philip Bernstein, Microsoft Research, Distinguished Scientist - Data Management, Exploration and Mining

Richard Catalano, Jr., University of Washington, Barly Dobb Professor - Social Development Research Group

Sue B. Clark, Pacific Northwest National Laboratory, Chief Science and Technology Officer and Battelle Fellow - Energy and Environment Directorate
Washington State University, Regents Professor - Department of Chemistry

Cynthia Dougherty, University of Washington, Professor of Biobehavioral Nursing and Health Informatics - School of Nursing
Adjunct Professor, UW School of Medicine - Division of Cardiology
Nurse Practitioner, VA Puget Sound Health Care System - Department of Cardiology

David Eaton, University of Washington, Associate Vice Provost, Office of Research and Professor, Environmental and Occupational Health Sciences

Thomas Marsh, Washington State University, Professor and IMPACT Director - School of Economic Sciences

Roger Myers, Aerojet Rocketdyne, Executive Director, retired

George "Pinky" Nelson, Western Washington University, Director - Science, Mathematics and Technology Education Program, retired

Mick Smerdon, Washington State University, Regents Professor of Biochemistry and Biophysics - School of Molecular Biosciences

Usha Varanasi, University of Washington, Distinguished Scholar in Residence - College of the Environment, Professor, Fishery and Chemistry Departments

Jud Virden, Jr., Pacific Northwest National Laboratory, Associate Laboratory Director for the Energy and Environment Directorate

Staff

Donna Gerardi Riordan
Executive Director

Devon Emily Thorsell
Program Coordinator

Preface

Climate change is one of the most important issues facing Washington State. It is altering the state's weather, climate, and shorelines. It is affecting agriculture, terrestrial and marine ecosystems, and human health. While many uncertainties remain, the prospect of major changes in weather, climate, oceanic acidity, and sea level is sufficiently clear that the state can and must prepare for the possibility of a drastically altered future.

Given its importance to our state, the Washington State Academy of Sciences decided to make climate change the focus of its 10th Annual Meeting and Symposium, which was held at the Museum of Flight in Seattle on September 14, 2017. This was the first time that the Academy opened its annual meeting and symposium to non-members, and it marked a new era in the organization's history. The objectives of the symposium were to:

- Provide background on the current state of knowledge of climate change effects on the state, and provide insight to the salient uncertainties.
- Pinpoint where the Academy can provide assistance in a timely way to the Governor and policy makers in the state.
- Disseminate a written summary and the presentations.
- Develop next steps for the Academy.

To accomplish these objectives, the eleven speakers, all leading experts regionally and nationally, focused on three topical areas: how climate has changed in the past in the Pacific Northwest and predictions of how it will change in the future (Chapter 1), the possible consequences of future climate change in Washington State (Chapter 2), and how the state can adapt to ongoing changes and prepare for future changes (Chapter 3). In addition, speakers were asked to reflect on what the Academy can do to help the state made decisions regarding climate change and its effects (Chapter 4).

I sincerely thank several people who were instrumental in the success of the annual meeting. The Academy's new executive director, Donna Gerardi Riordan, and its new program coordinator, Devon Emily Thorsell, organized and carried out the meeting flawlessly. Cliff Mass and Amy Snover of the University of Washington and Lynn Helbrecht from the Washington Department of Fish and Wildlife provided invaluable assistance in organizing the agenda. Seattle writer Steve Olson wrote the summary of the meeting. The Museum of Flight was a gracious and accommodating host.

Washington State has been a leader among the states in understanding and preparing for climate change, and the 10th Annual Meeting and Symposium of the Washington State Academy of Sciences brought together many of the people who have been at the forefront of this effort. The resulting evidence-based overview of climate change clearly illustrated the strong influence and potential and present impacts on ecosystems, energy, humans, and the economy in Washington state. The meeting served as a valuable reminder of the progress that has been made and the major challenges that lie before us; it also provided us with steps that can be taken to deal with these challenges.

Ron Thom

President Elect, Washington State Academy of Sciences

I

Climate Trends and Projections in Washington State

The climate has been changing in the Pacific Northwest, but so far the changes have been, for the most part, subtle and selective. Nick Bond, the Washington State Climatologist and a principal research scientist with the University of Washington's Joint Institute for the Study of Atmosphere and Ocean, summarized the observed trends to lay the groundwork for the symposium.

Average high temperatures and average low temperatures have been going up in the Pacific Northwest over the past century, with the largest increases for winter high temperatures and for winter and summer low temperatures (Figure 1-1). These trends have implications for "everything from agriculture to the forest ecosystems to human health," said Bond. For example, warmer temperatures increase the evaporation of water from the soil and the transpiration of water from plants into the atmosphere, which increases demands on irrigation.

Humidity levels also have been going up in the summer, Bond noted. "It's nothing like Mississippi, but it is a little stickier, a little warmer, in the summertime."

Precipitation amounts have not risen over the past century except in the spring (Figure 1-2). However, the snowpack measured at the end of the winter has declined somewhat, as would be expected with warmer winter temperatures, though it still exhibits great variability from year to year. Trends in snowpack also depend on where it is measured, since the average snowpack appears to be declining in some places but increasing in others.

The highest daily annual flow, which corresponds to flooding risk, is up on some rivers and streams but not all and again is marked by great variability. Similarly, the minimum streamflow, an indicator of drought, has been declining on some streams but not all.

The overall trend is also unclear for the wettest precipitation events along the West Coast of the United States and Canada. While there may be an upward trend in top precipitation events as measured in Forks and Aberdeen, the trend is not unmistakable. In addition, said Bond, a major question is whether changes are due to global climate change or to unrelated changes in global and regional circulation patterns.

Another way to measure the intensity of storms is to look at the height of ocean waves measured by buoys off the West Coast, but these measurements also do not show any strong trend over time.

The incidence of unusually hot days has not changed in western Washington or Oregon, though the heat spell that occurred in 2009 was by some measures the most intense on record. However, overnight heat events, where the temperature stays unusually warm overnight, have increased in western Washington and Oregon. Warm overnight temps in 2009 were particularly remarkable in terms of their duration, lasting for eight nights.

Finally, Bond observed that average sea level has gone up by about 8 inches in Seattle over the past century, or an average of about 2 millimeters per year, and the maximum high water mark has gone up even more (Figure 1-3). Sea surface temperature anomalies off the coast of the Pacific Northwest have also been increasing, with a particularly strong high-temperature anomaly (which Bond nicknamed "the blob," a term that became widely used in the media) in 2004-06.

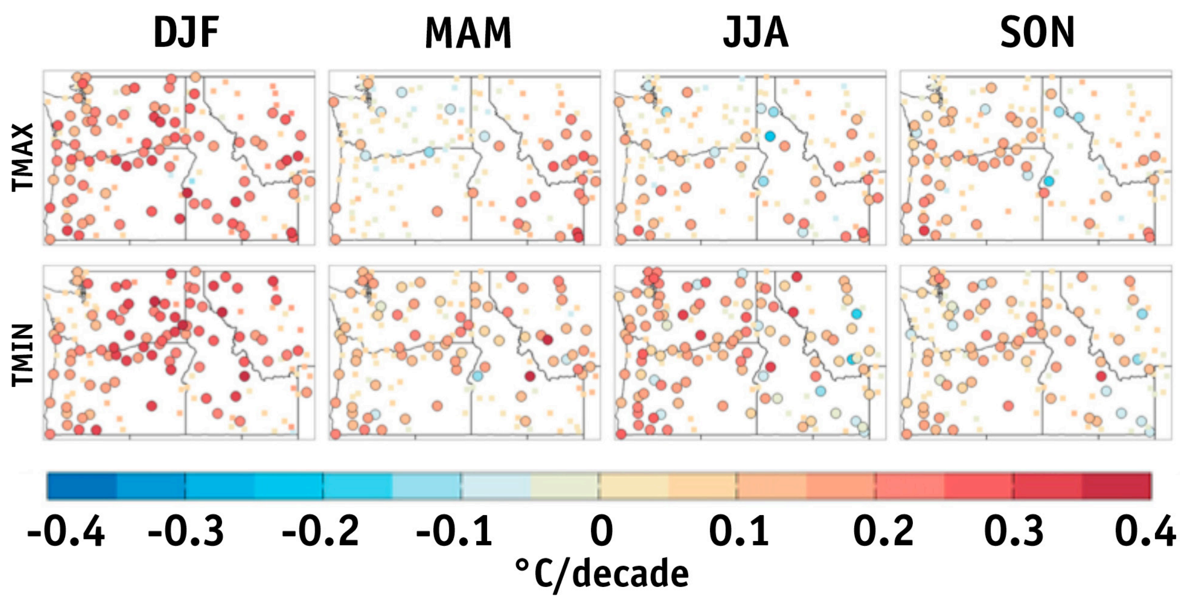


FIGURE 1-1 From 1920 to 2012, maximum temperatures (top row) increased most in the winter in Washington State, while minimum temperatures (bottom row) increased most in the winter and summer. Squares indicate lack of significant linear trends; circles are significant at 95 percent. Source: John T. Abatzoglou, David E. Rupp, and Philip W. Mote. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. *Journal of Climate* 27:2125-2142.

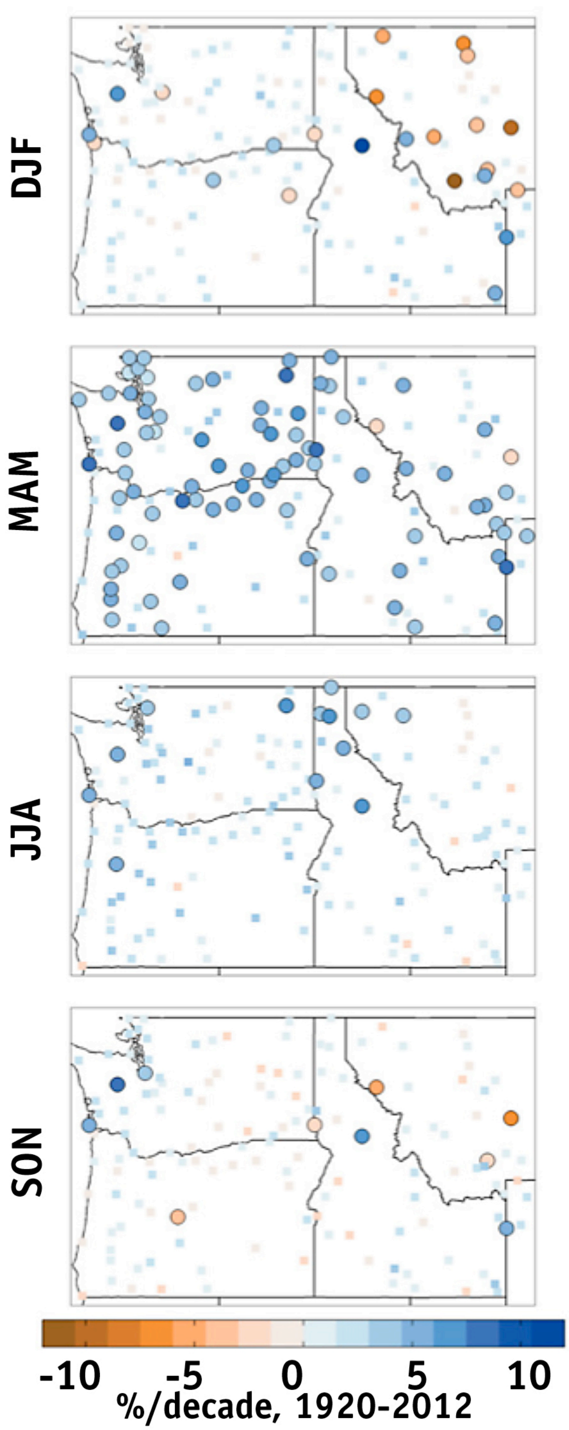


FIGURE 1-2 From 1920 to 2012, precipitation in Washington State increased most in the spring. Squares indicate lack of significant linear trends; circles are significant at 95 percent. Source: John T. Abatzoglou, David E. Rupp, and Philip W. Mote. 2014. Seasonal Climate Variability and Change in the Pacific Northwest of the United States. *Journal of Climate* 27:2125-2142.

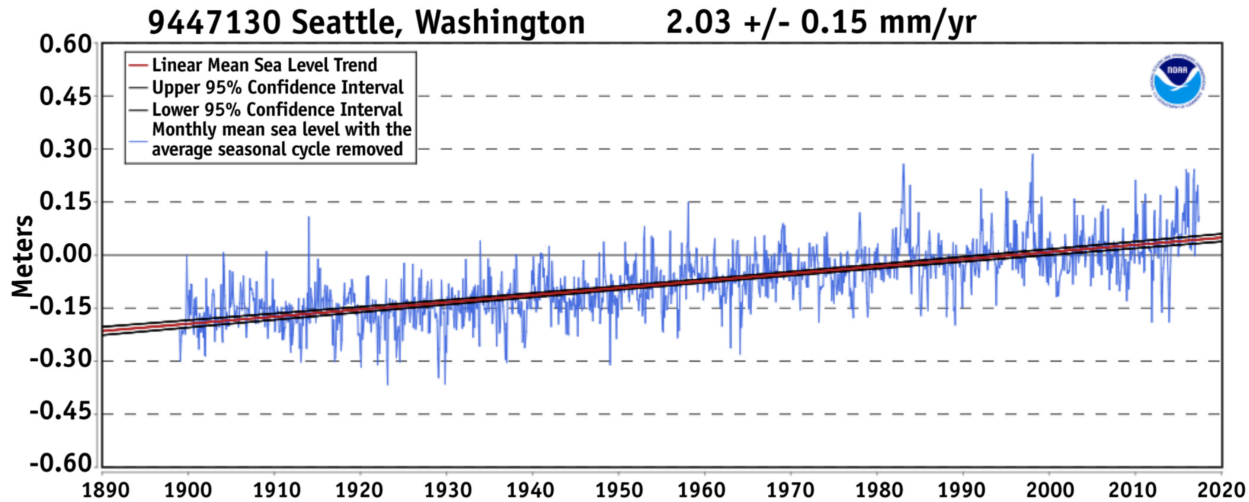


FIGURE 1-3 Sea level in Seattle has increased at a rate of about 2 millimeters per year since 1900. Source: National Oceanic and Atmospheric Administration.
(https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9447130)

Predicting the Future of Climate

The public and private sectors in Washington State are continually making decisions that depend on future climate trends. "I got a call once from Seattle Public Utilities," said Cliff Mass, professor of atmospheric sciences at the University of Washington. "They were installing drainage pipes that will be there for 75 years, and they wanted to know what size they should be. They were about to spend a quarter of a billion dollars on this. We need projections of future climate to be able to deal with resilience and adaptation. How are we going to be ready for what is going to happen by the end of the century?"

Today, global climate models (GCMs) provide a large-scale view of climate change impacts. But these models have a typical resolution of just 100 to 150 kilometers, which means that they are not able to include much of the detailed geography of the Pacific Northwest. Yet this geography has a critical influence on our climate, Mass pointed out. GCMs "don't have the Olympics in them. They don't have the Cascades. They don't have land-water contrast right. And that's a problem, because our meteorology is dominated by the effects of terrain and the land-water contrast. If you want to find out what the local implications of climate change are going to be, these GCMs are not going to do the trick."

One way to determine the regional implications of GCM forecasts is a technique known as dynamic downscaling. This approach involves using high-resolution regional or local climate models with boundary conditions driven by the output of GCMs. Regional and local climate models, which have much finer resolution than GCMs, can model how relatively small-scale elevation changes influence precipitation or the interactions between melting snow and solar radiation. For example, Mass showed the differences between global and regional climate models for the projected temperature change between the 1990s and 2090s (Figure 1-4). While both project extensive warming, the regional model shows much more severe warming in particular locations, largely because of enhanced melting of snow.

Regional models can point to potential surprises. For example, regional models predict much heavier springtime cloud cover in the 2090s than today. "June Gloom will get worse with global warming," said Mass, largely because pressure in the spring will decrease faster over land than over water, which will pull moisture from the Pacific Ocean into coastal British Columbia, Washington, and Oregon. Regional climate models also can indicate where changes are less likely. For example, they indicate that windstorms will not get stronger by the end of the century. However, Mass agreed with Bond that intense rainfall events are likely to increase and snowpacks are likely to decline, both of which will increase flooding.

Regional climate models are most reliable if they are run multiple times and in multiple forms. As with the models used to forecast weather, the resulting ensemble predictions help reveal the uncertainties of predictions and the probabilities of any one prediction being correct. Models can be run with different start dates, different ways of handling atmospheric physics, and various amounts of greenhouse gases. They also can be linked with hydrological models, air quality models, and other kinds of models to understand the implications of climate change, which policy makers then can factor into major decisions.

Mass suggested that regional resources should be combined to better understand the meteorology of Washington State and to prepare for the future. A Northwest Regional Climate Modeling Consortium could include regional government entities, state and federal agencies, foundations, academic institutions, tribes, and private sector companies, with decisions made by contributing stakeholders. Goals would be to acquire sufficient computer resources to perform GCM runs and filter out poor performers, develop increasingly sophisticated regional climate models, run dozens of high-resolution regional simulations extending 100 to 150 years into the future, apply sophisticated statistical post-processing, and incorporate ancillary modeling systems such as hydrological models. Amazon has already provided initial support for personnel and computer resources, but the effort is not sustainable without more support. "Regional climate modeling is essential for preparing our state and to let us know what's going to happen."

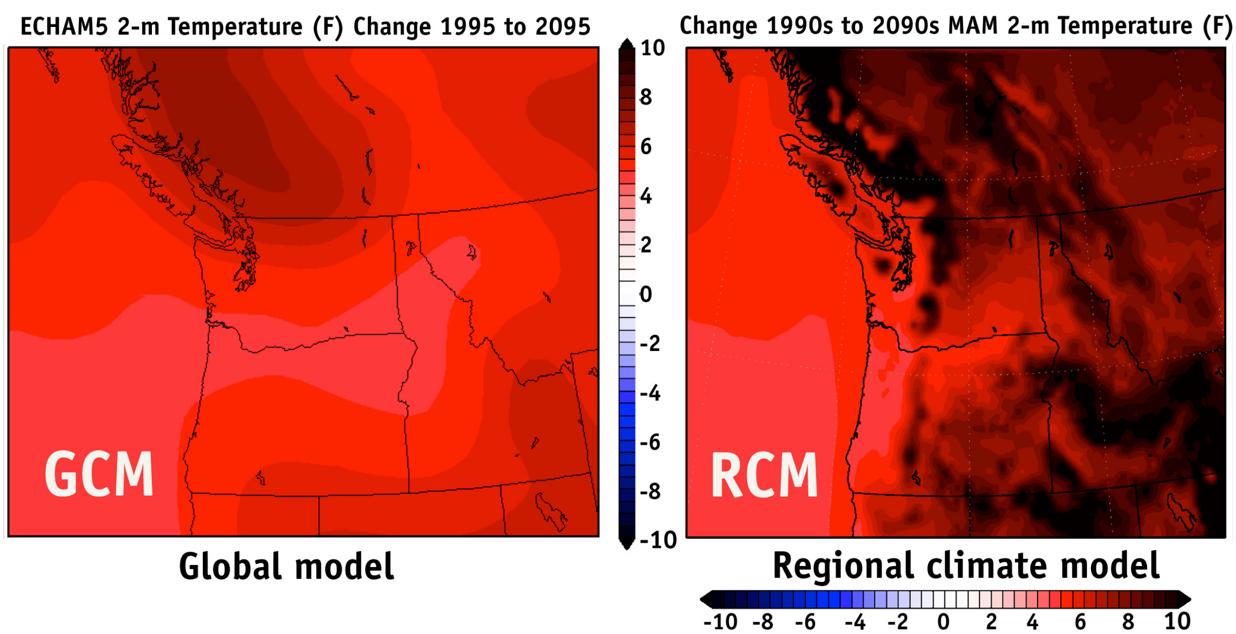


FIGURE 1-4 A regional climate model (right) contains much more detailed information on projected temperature increases from the 1990s to the 2090s than a global climate model (left). Available at cliffmass.blogspot.com/2015/09/regional-climate-prediction-crucial.html.

Modeling Atmospheric Rivers

Ruby Leung, a Battelle Fellow at the Pacific Northwest National Laboratory and affiliate scientist at the National Center for Atmospheric Research, looked more closely at a specific feature of the Northwest's weather. Atmospheric rivers are relatively narrow plumes of moisture in the atmosphere that originate in the tropical Pacific and produce copious rainfall when they hit North America, generally in the winter and spring (Figure 1-5). Because of their tropical origins, they are relatively warm and, in the Pacific Northwest, cause the mountain snowpack to melt rather than adding to snow levels. But Washington State typically does not need abundant warm precipitation in the wintertime, because the greatest demands for water are in the summer. "In years when we have more atmospheric rivers, you have less snowpack even though they dump a lot of precipitation," Leung said.

Leung and her colleagues, including Naomi Goldenson at the University of Washington, have been using global models that incorporate variable resolution to investigate the relationships between atmospheric rivers and snowpack in the western United States. Such models combine relatively coarse grids in some parts of the world, such as over the open oceans, with much finer grids in other parts of the world, such as over the complex topography and coastal areas of the Pacific Northwest. A model of this type that Leung and Goldenson have been using captures the general pattern of observed precipitation and snowpack in winter.

In the Pacific Northwest, three simulations that differ only by the initial conditions capture the observed relationship between atmosphere rivers and snowpack in winter. Years with more atmospheric rivers have less snowpack along the Cascades because the warm air mass after atmospheric rivers make landfall induces snowmelt. However, during spring, the relationships between atmospheric rivers and snowpack differ quite substantially among the three simulations, suggesting larger internal variability during spring than winter.

Overall, variable grid models are good at simulating the jet stream's location and strength, which influence atmospheric river frequency, Leung said, even with a larger grid size than the ones optimal for determining effects on land. At finer grid size, the model does capture the spatial variability of the precipitation much better than a coarser simulation, and these are the small-scale features that will determine such factors as the amounts of precipitation and the depth of the snowpack. Therefore, global variable resolution models offer an alternative approach to regional climate models for representing topographic effects in the Pacific Northwest. By using regional refinement, global variable resolution models provide more consistency between large-scale circulation features such as atmospheric rivers and their local impacts than regional models that rely on global models to provide large-scale boundary conditions.

As the above example shows, internal variability can contribute large uncertainty in projecting climate change in the Pacific Northwest as different runs of the climate model with perturbed initial conditions tend to produce quite different results in spring. Many modeling centers have produced projections of temperature and precipitation changes using different emission scenarios and perturbed initial conditions. "This kind of information is very useful for us to design our modeling approach to quantify uncertainty in projecting the future," said Leung.

In summary, with advances in computing and modeling, several high-resolution modeling approaches are now available for projecting regional climate change. Model projections continue to have uncertainties because of such factors as internal variability, and continued work is needed to develop approaches for ensemble modeling to quantify different sources of uncertainty. Nevertheless, many low- and high-resolution simulations are now available to provide planning guidance.

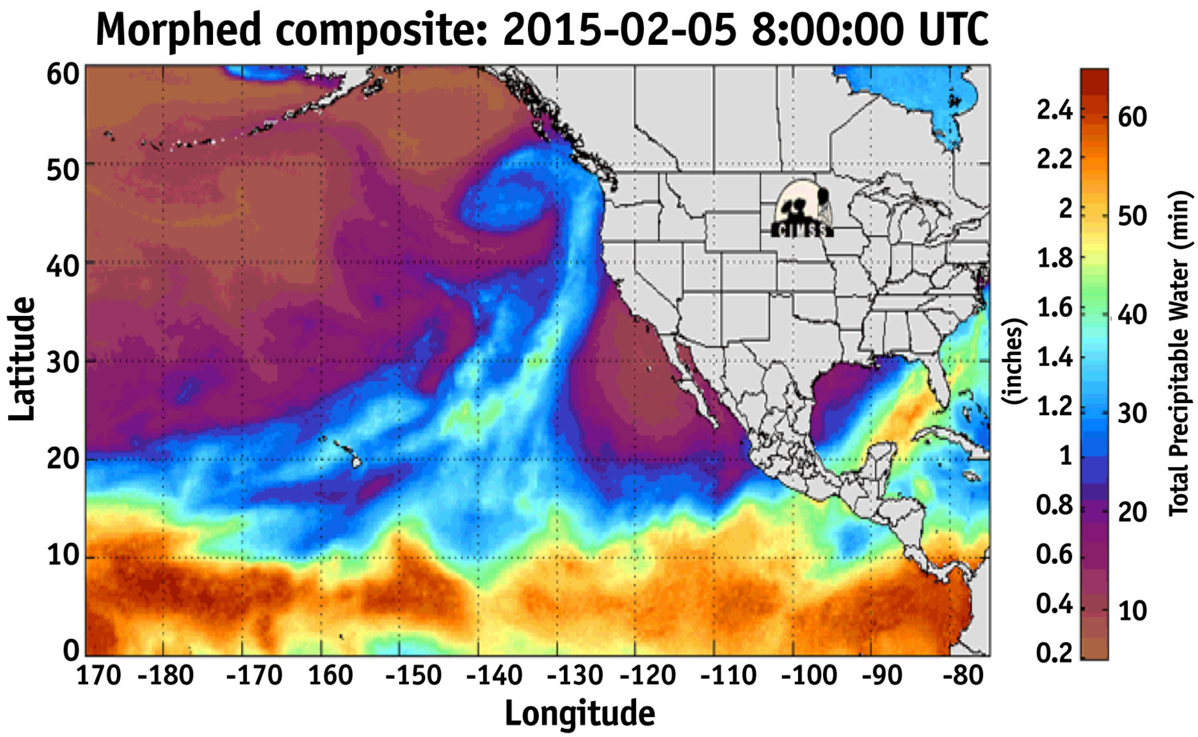


FIGURE 1-5 A plume of atmospheric moisture carried north from the tropics makes landfall in the Pacific Northwest on February 6, 2015. Source: CIMSS, University of Wisconsin-Madison.

PAGE LEFT
INTENTIONALLY BLANK

2

The Consequences of Climate Change in Washington State

Climate change will have consequences throughout Washington State on everything from agriculture to ocean chemistry to human health. Five presenters at the meeting looked at possible consequences and at what they could mean for residents of the state.

Water Resources and Agriculture in the Columbia River Basin

The Columbia River basin has multiple and competing uses for the river's water. Dams on the river and its tributaries generate hydropower, control floods, and shape navigation and recreation (Figure 2-1). Water drawn from the river and its tributaries serves municipal and industrial purposes. Water flows, temperatures, and chemistry affect the fish and other organisms that live in, on, and near the river.

However, the leading user of water out of the river is agriculture, observed Jennifer Adam, associate professor of civil and environmental engineering at Washington State University. More than 300 crop commodities are grown in Washington State, including 11 for which the state is the nation's leading producer. Livestock and crops together account for about $10 billion of the state's economic output per year, which is about 12 percent of the state's economy.

Every five years, the Washington State Department of Ecology's Office of the Columbia River (OCR) is required to submit a long-term (20-year) water supply and demand forecast to the state legislature. Washington State University has the lead responsibility for developing the forecast, which it does through a collaboration involving the University of Washington, the University of Utah, the Washington State Department of Ecology, and Aspect Consulting. Because of its long time horizon, the forecast has to take future projections of agricultural demands and climate change into account.

The forecast begins with a coupled simulation of the hydrologic cycle and crop growth. Different weather information can be used with the model, including ten future climate scenarios for the 2030s that correspond to different levels of greenhouse gases in the atmosphere. The results of this model are then routed through a model of the flow network in the Columbia Basin. Agricultural demand can be compared with the supply of water in years when water is plentiful and when it is scarce. In years of drought, various legal provisions limit the supply of water to particular users, and these legal provisions are included in the model. If curtailments are necessary, the reduced demand for water can be coupled to the hydrologic model to calculate new water flows and the impacts on crop yield.

Adam and her colleagues have used this approach to project the production of 40 crop groups into the future. The mix of crops that farmers plant is constantly changing, she observed, and crop mixes have a substantial effect on water demand. For example, wine grapes, which have become much more widely grown in Washington State, use much less water than do other crops. The seasonality of water supplies is also an important factor. Because of decreases in the snowpack, climate models suggest that more water will be available from November through May and less from June through October.

Interestingly, she said, the model forecasts a decrease in irrigation demand over the next 20 years if irrigated acreage is not increased. Part of this decrease comes from a shift toward crops that use less water, such as grapes. Part is due to increases in carbon dioxide in the atmosphere, which causes plants to use water more efficiently. Finally, part is due to the fact that farmers can plant earlier under warmer conditions, thus shifting irrigation earlier in the season when spring precipitation is projected to increase. Warmer temperatures will also cause plants to mature and be harvested more quickly, partly because of warmer temperature and partly because of the increase of carbon dioxide in the atmosphere, which has a fertilizing effect. The shift toward an earlier growing season may even make it possible for farmers to raise a second crop or a cover crop during the growing season, though this potential increase in double cropping and cover cropping was not included in the model. More efficient irrigation technology or better irrigation management could further reduce demand for water.

The model points toward some increase in water curtailments in the medium and high emissions scenarios. These curtailments will increase over time, particularly if emissions are high. However, the impact of curtailments is likely to be less in at least the near-term future than has sometimes been the case in the past because of offsetting factors. At some point, as temperature continues to increase, the impacts will go beyond the historical impacts. A new finding from these results shows that curtailments will likely increase during the early irrigation season as irrigation demand shifts earlier in the season. Even though water supply will also shift toward early in the season due to warming-related reduction in the snowpack, the early shift in irrigation demand may outpace shifts in some locations. This has implications for how reservoirs should be managed in the future.

Climate change impacts irrigated crop yield directly through changes in temperature and carbon dioxide concentrations. The modeled net effect is that yields of pasture grasses will increase, that perennials like apples and mint will see little change, and that some annuals like potatoes and corn will have reduced yields. Irrigated crop yield is also impacted indirectly by climate change through curtailment of water rights. The crop yield impacts of curtailment are reduced in the future as compared to the past because of increased carbon dioxide concentrations that allow the crops to make better use of the water and because warming means that the crops may be harvested before late season curtailment decisions are made.

The model still has uncertainties, Adam acknowledged. Not all categories of water rights are included, and information on some water rights is limited. Double cropping, cover cropping, changing groundwater levels, the fertilization effect of carbon dioxide and possible expansions of irrigated areas all could alter future projections. Other changes, such as growing different crops or different varieties of crops, also could alleviate or exacerbate water constraints.

FIGURE 2-1 The dams on the Columbia River and its tributaries profoundly shape water uses in the Columbia River basin (outlined in green). (Figure created by the US Army Corps).

Energy Systems

Many factors influence the impacts of weather and climate on energy systems, including water availability, heat waves, energy demand, public policies, and the operations of the distribution network. Ian Kraucunas, director of the Atmospheric Sciences and Global Change Division at Pacific Northwest National Laboratory, focused on the electric grid, which can be severely stressed by heat waves. Warmer air reduces the efficiency of power plants, causes more resistance in transmission lines, threatens the functioning of transformers, and increases the demand for space cooling — and all of these factors will be worsened by climate change.

In addition to heat waves, the electric grid in the Pacific Northwest will be stressed by reductions in mountain snowpack, which will reduce hydropower availability during summer months, when the demand for electricity for space cooling is high. In other regions where fossil fuel power plants are dominant, warmer water is reducing the efficiency of turbines. In addition, many future energy scenarios foresee greater reliance on bioenergy, which makes further demands on water supplies.

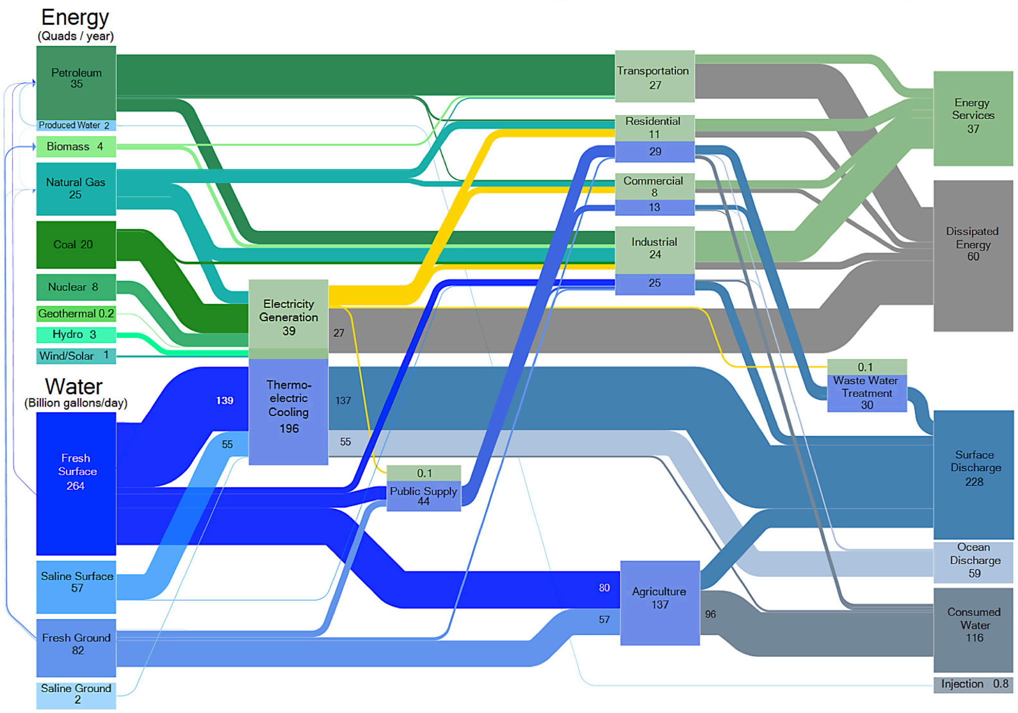
A reduction of available hydropower in the summertime could have widespread consequences. Electrical energy systems in the western United States are interconnected, so that sometimes the Pacific Northwest and Rocky Mountain states are sending energy to California while at other times California is exporting power to other parts of the West. Climatic fluctuations in different parts of the West often balance each other out, Kraucunas pointed out. For instance, when the Pacific Northwest is relatively wet and cool, the Southwest is often dry and hot, which means that excess hydropower can be sent south to make up for the reduced efficiency of fossil fuel plants. However, in climate scenarios where the entire West is dry, regional models show that energy supplies could fall 6 percent below demand. Though electric grid operators have ways of making up for such shortfalls, “it’s an indication of the vulnerability of the system,” Kraucunas said.

For the United States as a whole, energy demand is projected to go down under climatic warming due to reduced need for space heating in the winter and improved building technologies. However, the peak energy demand is expected to go up in most locations due to higher maximum summer temperatures, which are the same weather events that lead to reductions in energy supply. In addition, demand for space cooling could soar as temperatures rise and as reliance on air conditioning increases. Energy companies need to build their systems to accommodate the worst event that could happen, which would require increased investments to prepare for future heat waves. Yet they would be selling less energy overall. “That’s a pinch point that they’re very worried about,” said Kraucunas.

The energy and water systems are tightly connected (Figure 2-2). For example, electricity generation requires large quantities of fresh and saline surface water, with most of this water being discharged back into the environment at higher temperatures. In contrast, the agriculture system uses large amounts of both surface water and groundwater but only returns some of this water to the environment. Water and energy systems also interact with land use. For example, increased deforestation can have the effect of increasing the albedo of the land surface, reflecting more sunlight into space, and slowing the rate of temperature increases. But, warned Kraucunas, “I’m not sure that that’s a landscape we all want to live on.”

Tradeoffs also come into play if the use of biofuels increases dramatically. Growing such fuels will require water, which could increase the stress on energy systems and other water demands. Similarly, greater use of solar energy will require changes in land use, which can impact the ecology of an area. “It’s important to keep these tradeoffs in mind,” he said. Careful analysis and modeling with high resolutions will be needed to understand the tradeoffs involved, improve efficiencies, and make good policy decisions.

2011 Estimated U.S. Energy-Water Flow Diagram



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

FIGURE 2-2 The generation and use of energy is tightly linked to the use of water. Source: U.S. Department of Energy. 2014. *The Water-Energy Nexus: Challenges and Opportunities.* Washington, DC: U.S. Department of Energy.

Ocean Acidification

The ocean has taken up about 28 percent of the carbon dioxide released by industry and deforestation. The resulting rate of change in ocean acidity is unprecedented in at least the last 25 million years (Figure 2-3). “We haven’t seen anything like this,” said Terrie Klinger, Stan and Alta Barer Endowed Professor in Sustainability Science at the University of Washington.

Evidence from laboratory and field studies indicates that changes in ocean acidity could have multiple biological effects, from the lowest to the highest trophic levels and across multiple habitats, including biogenic habitats such as corals. The shells of planktonic organisms are thinner under ocean acidification conditions. Chitinous organisms, such as krill and shrimp, are negatively affected as well. Bivalve shells and the filaments by which they attach to rocks are weaker under acidification. Thinner shells make mussels more vulnerable to predation. Mortality of oysters and of Dungeness crab larvae and juveniles increases under ocean acidification conditions. “This is likely to have economic effects in Washington State,” said Klinger.

Copper rockfish, which are abundant in Puget Sound, and other fish show changes in behavior under ocean acidification conditions. Some fish lose their lateralization abilities, which affects their swimming ability — this is a surprise that would not have been predicted. Pink salmon show dose-dependent reductions in critical life-history and behavioral traits, and juvenile salmon lose their ability to detect predators.

Another surprise, observed Klinger, is that harmful algae become more toxic and grow faster under ocean acidification conditions, though the reasons for these changes are not yet fully understood. In this case, acidification appears to work synergistically with other stressors, such as increased temperature, less dissolved oxygen, and changes in nutrient concentrations.

In Washington, threats to valued resources and iconic species have spurred action. The oyster industry has been working with the scientific community to communicate the story of ocean acidification in Washington State, and the political leadership of the state has taken on this issue. "Washington State leads the nation in its response to ocean acidification, and what we do here is being replicated in other states, including California, Maine, and Massachusetts," said Klinger.

She concluded with several research priorities for Washington State:

- Understand the status and trends of acidification in Washington's marine waters.
- Quantify the relative contribution of different acidifying factors in Washington's marine waters.
- Describe the biological responses of local species to acidification and associated stressors.
- Describe real-time corrosive seawater conditions.
- Develop short-term forecasts and long-term projections of global and local acidification effects.

"We do have choices," said Klinger. "Our emission scenarios will make a difference in how the ocean responds to climate." About 250 million years ago an extinction event that killed 90 percent of the living things on earth was associated with acidification. "The paleontological evidence tells us that this is a serious threat that we need to pay attention to."

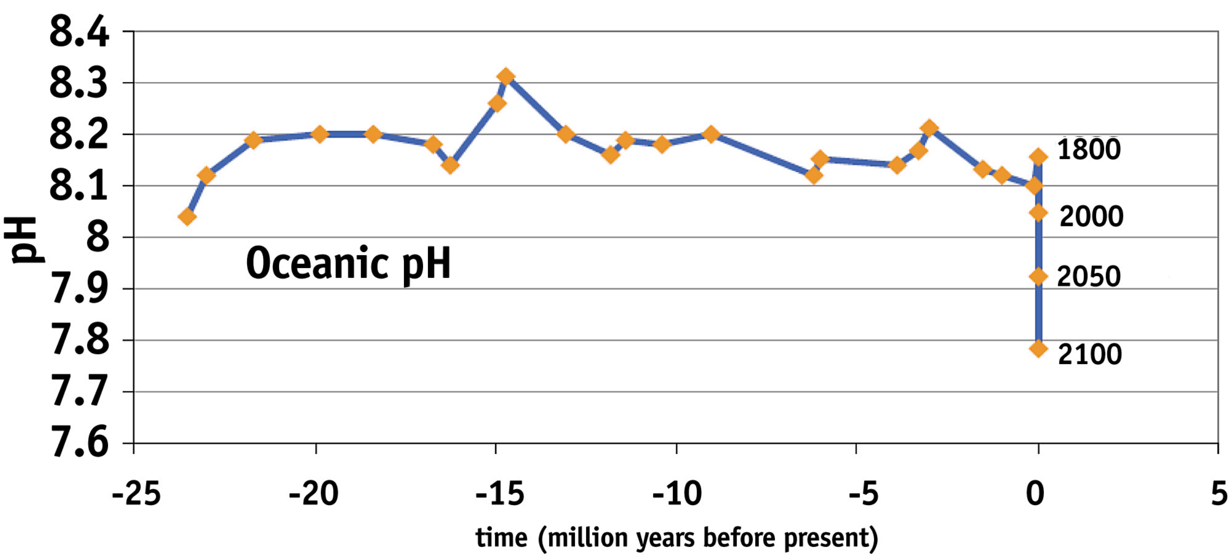


FIGURE 2-3 The oceans are projected to become more acidic in the 21st century than they have been for millions of years. Source: EUR-OCEANS, 2007.

Diseases in Fish

Most of what is known about diseases in fish comes from experience with cultured fish, observed James Winton, senior scientist, emeritus, in the Fish Health Research Section at the Western Fisheries Research Center of the U.S. Geological Survey. Knowledge about diseases of fish in the wild is much less certain. Features of the host, the pathogen, and the environment determine the outcomes of a disease. In addition, stress reduces immunity in fish, resulting in higher disease burdens and mortality.

A variety of factors have contributed to observations of a global increase in diseases of fish in the wild. Better diagnostic assays are being used to gauge the health of fish, and surveys of new species or geographic areas are being conducted. The global growth of aquaculture is raising fish in high densities where they have not been raised before, which has resulted in disease outbreaks. The fish trade, anglers, ballast water in ships, and other mechanisms have increased the movement of fish, pathogens, and carriers of disease organisms. The spread of nonnative species, losses of habitat, and changes in the forage base have imposed biotic stresses on ecosystems. And anthropogenic inputs of contaminants and toxins as well as changes in water quality, flows, and temperature can all harm the health of fish.

Because fish are cold-blooded, temperature is the most important environmental factor affecting the severity of disease as it controls both the growth rate of infectious agents and the speed or strength of the immune response. As a classic example of research on temperature changes, Winton cited a study of water temperature on coho salmon infected in the laboratory with *Flavobacterium columnare.* In tanks of different temperatures, fish were able to survive temperatures ranging from optimal to high for Pacific salmon. But as the temperature increased, mortality quickly rose to 100 percent. "Bacteria and parasites can grow much more quickly [at higher temperatures], and the immune system of the fish isn't able to keep up."

The effects of rising temperature also can be observed in the wild. In 2002, more than 35,000 returning adult chinook, coho, and steelhead died in the Klamath River when upriver irrigators were provided with water while downriver flows for fish were reduced during a drought that caused 50-year low flows and high temperatures. As the fish were trapped in pools by low water flows and temperature blocks, they were attacked by the bacterium that causes columnaris disease, which attacks the gills and skin. This was compounded by ichthyophthiriasis disease, which is a parasite that also causes problems in aquariums at higher temperatures. A similar condition occurred on the Columbia River in 2015, resulting in the loss of approximately 450,000 adult sockeye, said Winton. "Warm surface water was feeding the fish ladders, so the fish wouldn't enter the ladders. They sat between the dams where they became senescent, infected each other with columnaris or other pathogens, and died by the hundreds of thousands." Losses were particularly great — more than 90 percent in some cases — with stocks of sockeye salmon that migrated later in the summer when the water was particularly warm (Figure 2-4).

Temperatures are rising faster in the Arctic than they are farther south, and the effects on fish have been drastic. Since the 1980s, subsistence fisheries in several locations have begun to encounter more and more fish that are not suitable for human consumption. For example, returning chinook salmon in the Yukon River have been found to be infected with ichthyophoniasis, with a steady increase in severity as the fish move upriver, followed by a loss of infected fish as they neared the completion of their migration more than 1,000 miles from the ocean. Laboratory investigations of the effects of temperature have revealed a loss of swimming stamina and increase in death caused by lesions in the heart that reduce cardiac function. "There's evidence from both experimental work and field work that this particular disease, and particularly these warming temperatures now common in the Yukon Rover, are causing a significant level of pre-spawning mortality."

As climate change progresses, the growth rate and types of pathogens, the host immune response to disease, the distribution of vectors, reservoirs, and carriers, and the density or distribution of susceptible species will all continue to change, said Winton. In addition, the physical habitat will change in ways that cause stress or affect the ecology of disease. For example, high winter water flows could scour out the nests that fish build. Also, water at higher temperatures reduces the metabolic efficiency of fish and contains less dissolved oxygen.

"The question is, how fast is it going to change and how fast will fish adapt?" said Winton. If 50-year events start happening much more frequently, certain fish stocks are likely to become extinct. Many of Winton's colleagues "think that salmon will go extinct in many rivers of the Northwest that are not provided with either dams or other ways to mitigate for flows and temperatures."

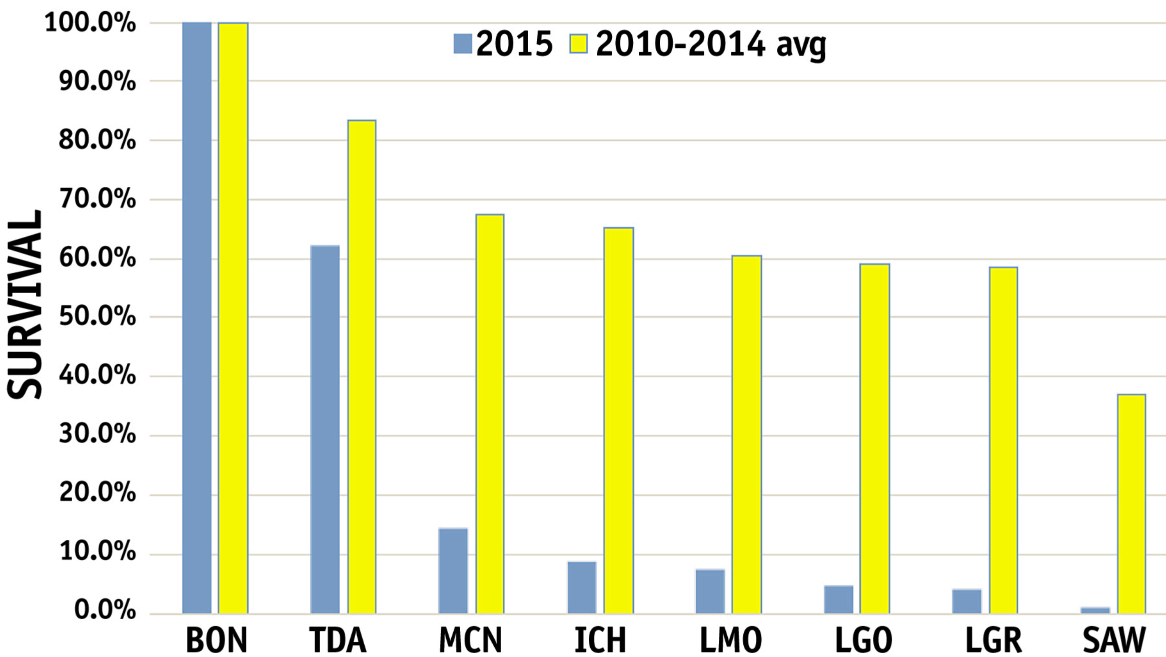


FIGURE 2-4 The proportion of tagged Snake River sockeye salmon that reached successive detection points at Columbia River dams in 2015 (blue) was much smaller than the average from the previous five years (yellow). Source: NOAA Fisheries 2015 Adult Sockeye Salmon Passage Report http://www.westcoast.fisheries.noaa.gov/publications/hydropower/fcrps/2015_adult_sockeye_salmon_passage_report.pdf

Human health

The vulnerability of human health to climate change varies dramatically from place to place, observed Kristie Ebi, Rohm and Haas Endowed Professor in Public Health Sciences at the University of Washington. Already, some underprivileged communities in Washington State are experiencing greater impacts than more privileged communities. "Every location has its strengths, and everyplace has its challenges, and these will interact with climate change," she said.

Among the many impacts of climate change on human health are heat-related illnesses and death (Figure 2-5). During a heat wave in Chicago in 1995, 700 more people died than would have been expected during that time of year — so many that bodies had to be stored in refrigerated trucks when the coroner's office filled to capacity. Heat waves in Europe in the summer of 2003 were responsible for 70,000 excess deaths. Beyond mortality, climate change is projected to be associated with substantial losses in productivity due to heat, such as for outdoor workers . Not just economic and health systems but entire communities are stressed by such events, said Ebi.

Ozone is a lung irritant that forms when pollutants interact with sunlight, and the rate at which this reaction takes place depends on temperature. Models project that ozone levels will increase substantially in the United States by 2030, which will increase the number of premature deaths caused by ozone. Even "Seattle could start seeing an increase in excess deaths," said Ebi. "As we have more clear, sunny days, our ozone concentrations will go up, and that will affect our health."

Higher levels of carbon dioxide in the atmosphere and warmer temperatures lead to more pollen in the atmosphere, which increases problems with allergies. Relatively few people in western Washington have air conditioning, which means that they have to open their windows to stay cool, but this increases indoor ozone and pollen levels.

Climate change is expected to increase the risk for a wide variety of infectious diseases, including Lyme disease, dengue fever, and leishmaniasis. Mosquitos, for example, are breeding and spreading diseases in more places as temperature and moisture increase. The mosquito species capable of carrying the Zika and dengue viruses is spreading northward and westward, and "it is just a question of when" it appears in western Washington, said Ebi. Similarly, Lyme disease recently emerged in Canada and is now spreading rapidly there. Projections show that it could become much more widespread as rising temperatures allow the ticks that carry it to continue to proliferate. Because few physicians in Canada have yet seen cases of Lyme disease, diagnoses are being missed, which means the disease can progress. "That illustrates the challenges we're going to face," said Ebi. "It's not just doing better surveillance. It's thinking much more broadly about how we work with our health care systems."

As an example of another study of the unexpected ways in which climate can affect health, Ebi cited a study in Sweden showing that calls to nurses for advice on gastrointestinal disorders go up as the number of consecutive wet days increases. Despite good water treatment systems, pathogens get washed into waterways with heavier precipitation, which increases disease transmission.

Anchorage recently experienced its first outbreak of *Vibrio parahaemolyticus* infections, which are caused by eating raw oysters, when water temperatures in Prince William Sound increased above the threshold for replication of the pathogen. Cereal crops grow faster and are less nutritious when grown under higher levels of carbon dioxide in the atmosphere. And air travel can spread diseases around the globe more quickly, allowing diseases to become established in new areas. "We're going to have surprises and we need to have much stronger health systems to be prepared to manage them," said Ebi.

All of these impacts and many more depend on the policy decisions being made today. “Today’s emissions are tomorrow’s temperatures, and the better we are at controlling our emissions now, the less we’re going to have to cope with later in this century.”

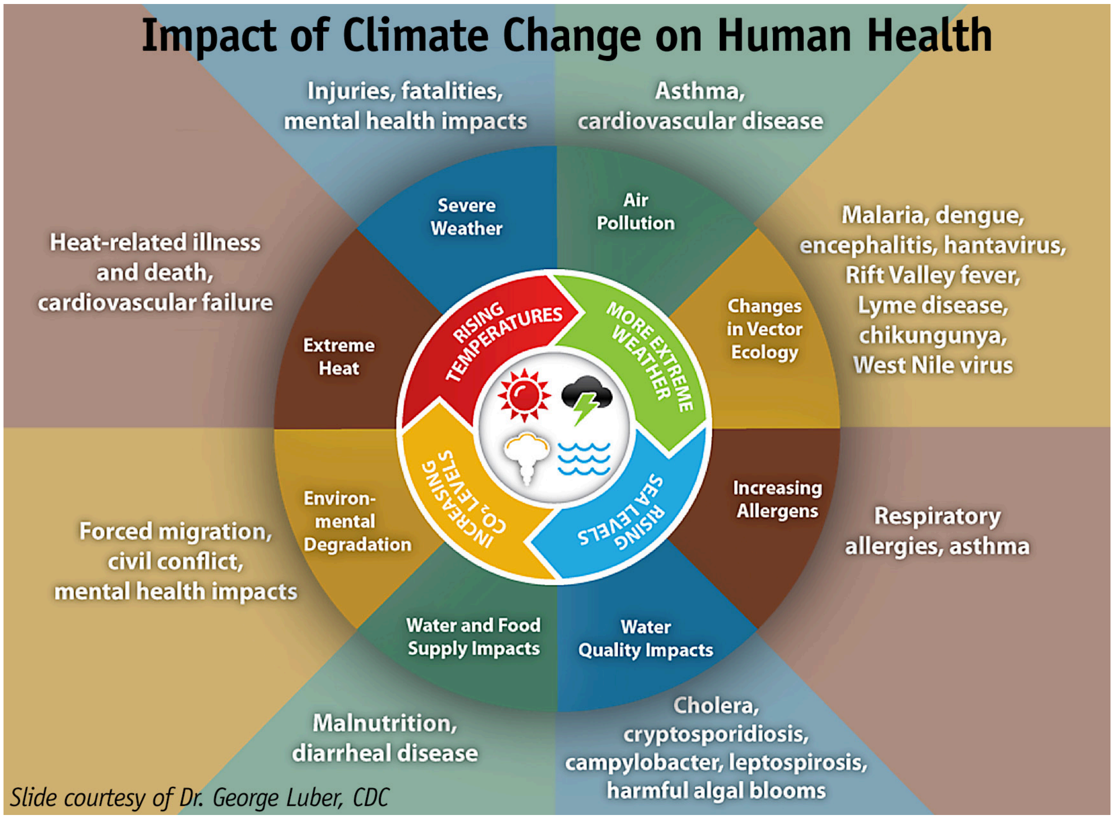


FIGURE 2-5 Climate change has a wide variety of direct and indirect effects on human health. Available at https://www.cdc.gov/climateandhealth/effects/default.htm.

3

Preparing for Climate Change in Washington State

There are two ways to manage climate risks, observed Joe Casola, deputy director of the Climate Impacts Group at the University of Washington. The first is to mitigate future climate change by reducing greenhouse gas emissions. The second is to adapt to climate change by anticipating and preparing for its impact.

Washington State has been doing both, Casola reported. Between 1990 and 2013, Washington State's greenhouse gas emissions rose by 7 percent (Figure 3-1). However, during that time, the state's population rose from slightly less than 5 million people to about 7 million people, so emissions per capita have dropped. The state has made commitments to achieve absolute reductions, with milestones for 2020, 2035, and 2050, and in 2016 the Department of Ecology made recommendations to the legislature to make the reduction targets more ambitious, including an 80 percent reduction by 2050, which is the target California has adopted (Figure 3-2).

Washington emits less than a quarter of one percent of the world's total greenhouse gas emissions, but it must still bear the impacts of global climate change — and "some of those risks may kick in at lower levels of warming than we thought in the early 2000s, when the original targets were made," said Casola. Organizations typically prepare for change by defining the problem, identifying and assessing options, implementing solutions, monitoring outcomes, and evaluating results. For climate change, defining the problem generally involves some kind of vulnerability analysis, which has occurred not only at the state level in Washington but in some cases at the local level. Less activity so far has focused on identifying and assessing options and implementing solutions, Casola noted, and changing operations and monitoring the results are even less common.

The Climate Impacts Group at the University of Washington is helping organizations go through the entire cycle of preparation, said Casola. It does this in part by investigating how climate affects systems that people care about, whether health, water, forests, ecosystems, or the many other systems that will be impacted by climate change. Knowledge about the sensitivity of these systems to climate change is often based on historical experience, and this knowledge is often held institutionally by those who manage resources or do research on the system. "You have to talk to experts with a wide range of backgrounds . . . to find out about climate sensitivity of resources," said Casola.

The second area of focus for the Climate Impacts Group is investigating what can be expected for future climate. This requires knowing both about natural variability and forced changes, which are superimposed on each other. As climate changes, average conditions may still lie within the envelope of historical experience. But when an unusual year is superimposed on a changing climate, the weather can become unprecedented, and as climate change progresses this will become more and more common.

The third approach is to figure out which solution options are available and most appropriate and when they should be instituted. The knowledge base to make such judgments is often substantially weaker than in the first two areas. It usually requires consideration of costs, the policy landscape, risk tolerance, and values. Options may need to be prioritized, and priorities may change as circumstances change.

Many climate resilience activities are occurring in Washington State, Casola noted, led by a large number of organizations and agencies working across sectors, across levels of governance, and at different scales. Among state agencies, activities related to health, ecosystems, oceans, water, agriculture, forests, infrastructure, research, communications, and public engagement are all taking place, and efforts have been made to coordinate these activities into an integrated climate response strategy. But "not all of the agencies are in the same place," said Casola. "The departments that have done more can help lower the bar for resources or for investments for those that are just starting."

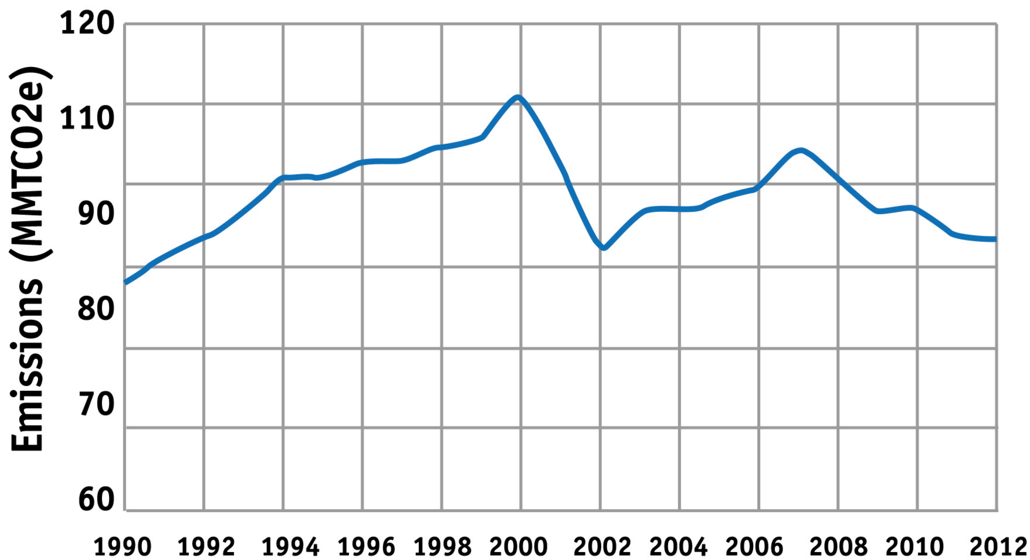


FIGURE 3-1 Washington State's greenhouse gas emissions increased about 7 percent from 1990 to 2013. The dramatic decline in the early 20th century resulted largely from the contraction of the state's aluminum industry. Source: Washington State Department of Ecology.

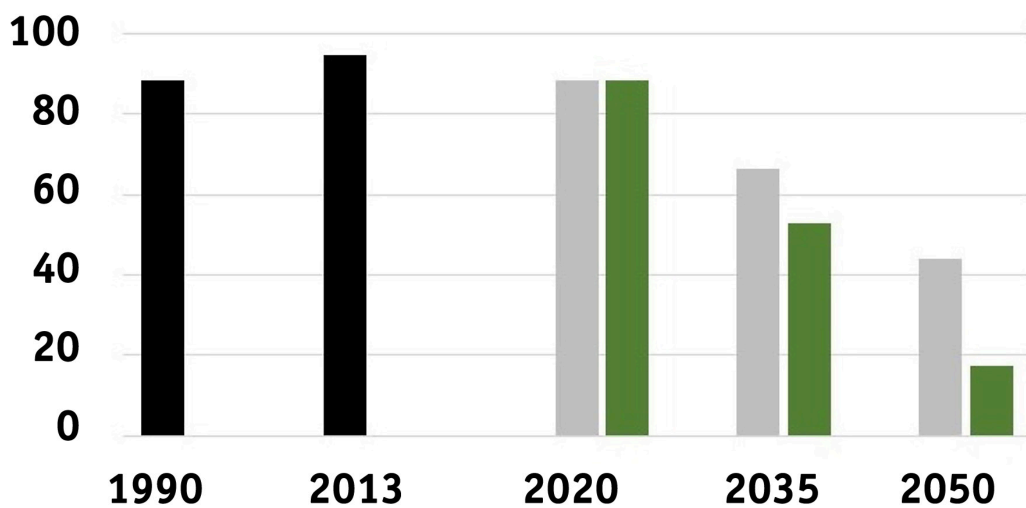


FIGURE 3-2 The target for emissions reductions in Washington State is to achieve 1990 emissions in the year 2000, with further reductions of 25 percent and 50 percent by 2035 and 2050, respectively. Recommended targets are 40 percent and 80 percent of 1990 emissions by 2035 and 2050.

Mitigation and adaptation

Local, state, national, and international agreements to reduce the emissions that lead to climate change are laudable. But mitigation "can be a tough nut to crack," said Jonathan Yoder, professor in the School of Economic Sciences at Washington State University. Reduced emissions are a public good, and when benefits are diffuse, people have powerful incentives to become free riders. In other words, they can enjoy the benefits of that good while trying not to pay for it. "Everyone wants somebody else to pay for mitigation," said Yoder. Mitigation agreements will continue to occur, but they tend to be fragile — "for example, countries dropping out of international global climate change agreements."

Adaptation is more promising. As a simple example, said Yoder, consider air conditioning. Deaths associated with hot weather have declined dramatically in recent decades because of air conditioning, he noted. Most people have the resources to buy and use an air conditioner, and they will have increasing incentives to do so as temperatures increase. At the same time, tradeoffs are involved, since space cooling is a major driver of energy consumption, which enhances climate change.

Various studies suggest that adaptation might reduce the economic impacts of climate change substantially, said Yoder. Incentives to adapt can be especially strong when the benefits and costs are aligned — like with air conditioning. Another example is seasonal timing of crop planting, where farmers plant earlier in response to earlier spring warming and related changes in weather.

Public policy and investments are important when the benefits are more diffuse or relevant information is costly to acquire or interpret. Agriculture again provides an example in Washington State, where changes in water law and policies may be necessary to give irrigators the flexibility to legally irrigate their crops earlier in the summer in response to warmer spring weather. As another example of large-scale coordinated adaptation to expected changes in the water cycle, Yoder pointed to the Yakima basin, which faces a declining snowpack that will increase the frequency and magnitude of irrigation water curtailments. In response, the proposed Yakima Basin Integrated Plan includes augmented water storage, water market improvements, and other adaptation steps (Figure 3-3). As part of his research on water use in the Yakima basin, Yoder and his colleagues have been exploring how improving the infrastructure for market transactions can reduce the economic consequences of water curtailments by allowing water to be moved to more valued uses and away from less valued uses. In general, he said, structural approaches and institutional approaches can substitute for each other — and both will become more valuable under climate change — but both require effort and resources, and tradeoffs abound.

Another example involves wildfires. Considerable research is being done on changes in wildfire regimes as climate and natural ecosystems change and as property is developed in wildfire-prone areas. Research indicates that development in fire-prone areas is leading to substantial increases in the costs of wildfire suppression, as much or more than the contributions from the dryness of fuels and other factors. While fuel management of forests in the form of prescribed fires or mechanical thinning can have local effects on fire severity, existing research shows little evidence that it has aggregate effects on costs or other outcomes like acres burned, Yoder said. Incentives for public land managers are to treat as many acres as possible rather than focusing on the acres that are at highest risk for fires, which may lead to lower effectiveness.

"Incentives matter for outcomes," said Yoder, and that applies just as much to climate mitigation and adaptation as it does in other domains of life.

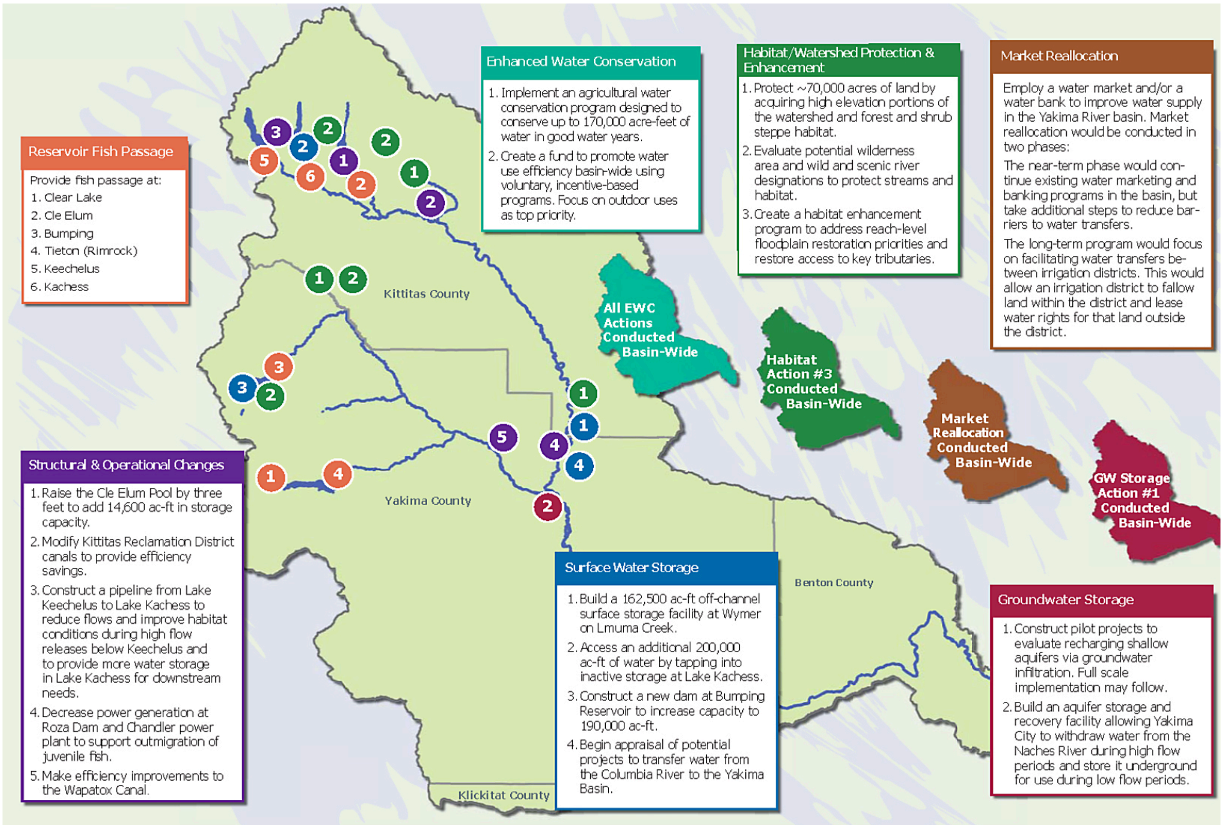


FIGURE 3-3 The Yakima Basin Integrated Water Resource Management Plan was developed by representatives from the Yakama Nation, irrigation districts, environmental organizations, and federal, state, county, and city governments to achieve consensus on the needs and uses of water in the Yakima River basin. Source: Available at https://www.usbr.gov/pn/programs/yrbwep/reports/FPEIS/fpeis.pdf.

From restoration to resilience

From 2012 to 2015 the western United States and northeastern Pacific Ocean experienced a sustained heatwave, which may have been a "dress rehearsal of what the future may hold for the region," said John Stein, chair of the science panel for the Puget Sound Partnership and scientist emeritus with NOAA Fisheries. Using the Skagit River as an example, Stein noted that water flows were well below normal in the summer of 2015. Meanwhile, temperatures in Padilla Bay north of the river were well above normal, which contributed to a major increase in the numbers of jellyfish offshore. In the summer of 2017 the Skagit River was closed to all fishing due to very low fish returns, in part because of the warm weather from two years before, and the numbers of juvenile salmon in the ocean were among the lowest on record. "It takes the biology a while to catch up with the physics," said Stein.

The Puget Sound Partnership is focused on the recovery of the sound and its relationship to the economy, ecology, and human well-being. The challenge is daunting, Stein observed, because of both climate change and human population growth. The Seattle metropolitan area is adding more than 1,000 new residents each week. "We can't talk about climate change without talking about population growth," said Stein.

The major challenges facing Puget Sound are building the support for actions to maintain and improve ecosystem services in the face of climate change and population growth and restoration at a scale that yields meaningful results (Figure 3-4). The region has seen progress, he emphasized. Restoration of the Elwha, Nisqually, Snohomish, and Skagit estuaries, removal of shoreline armoring, and reestablishment of sediment sources demonstrate what is possible. But the level of restoration that has taken place to date is insufficient to keep up with the stresses imposed by human population growth and climate change, Stein acknowledged. The opportunities for restoration on public lands are limited, which means that public-private partnerships will increasingly be necessarily. Broader support will be needed to stop the decline of the sound.

Perhaps restoration of the sound should be seen not as the goal but as a tool, Stein said. If resilience is the ultimate goal, the way forward may be to identify the path along which change is most acceptable. For example, slowing the pace of change so that ecosystems are not so susceptible to damage may be the optimum objective. In that case, important questions include:

- What are the key ecosystem vulnerabilities to climate change, ocean acidification, population growth, and development?
- What are the projected levels of inundation from sea level rise, surge, and waves?
- What ecosystem conditions can be forecast using an integrated ecosystem model?
- Given a changing climate, are restoration actions effective?
- What is the impact of different incentives on peoples' behavior? Are behaviors changing?
- How can natural and social science information be integrated in tools to support decision making?

On this last question, Stein noted that the natural sciences are certainly needed to answer these and other questions. But the social sciences are also needed to understand people's behaviors and how they might be persuaded to change.

Building the case to restore and protect ecosystem processes at the scale needed to meet the challenge will require robust public-private partnerships and creative solutions, Stein concluded. Restoration should be used as a tool to build a resilient Puget Sound that supports the economy, society, and future generations.

Goal	Ranking of Climate Risk to Vital Signs		
	High Risk	Moderate Risk	Low Risk
Water quantity	Summer stream flows		
Water quality	Freshwater quality Marine water quality Marine sediment quality	Toxics in fish	
Protect and restore habitat	Floodplains Estuaries Shoreline armoring		Eelgrass Land development and cover
Species and food web	Chinook salmon Orca Pacific Herring	Birds	
Healthy human population	Air quality Drinking water Locally harvestable foods Onsite sewage systems Outdoor activity Shellfish beds		
Human quality of life	Cultural wellbeing Economic vitality Sense of place	Good governance	Sound stewardship

FIGURE 3-4 The Puget Sound Partnership has conducted a preliminary climate vulnerability assessment that categorizes risk from climate change on the suite of indicators that the partnership is using to gauge ecosystem status and trends. Source: Siemann, D., and L. Whitely Binder. 2017. Preliminary Climate Change Assessment for Puget Sound Partnership. A Collaboration of Puget Sound Partnership and the University of Washington Climate Impacts Group. Seattle, WA.

4

Possible Actions by the Washington State Academy of Sciences

In the final session of the 10th Annual Meeting and Symposium of the Washington State Academy of Sciences — and at times earlier in the event — symposium participants discussed what the Academy can do to help the state prepare for and respond to climate change.

Working Toward Solutions

The Washington Academy of Sciences is particularly well positioned to deal with some of the contentious issues surrounding climate change. Yoder pointed out that it could detail the impacts of climate change and the costs and benefits of both mitigation and adaptation in a neutral but policy-relevant way. It could form blue-ribbon panels for science reviews and provide information to support governance decisions. He recommended keeping an eye on the following research areas:

- Innovations at the technology-institution nexus
- Public policies to facilitate private adaptation
- Changes in natural capital due to climate change in Washington, such as changes in timber value from bark beetle infestations and from fires
- Natural capital portfolio management in the face of change

Casola suggested that the Academy could have a more formal engagement with the state agencies that are working on adaptation, finding out what agencies need and helping to meet those needs. The Academy also could focus on tough sectoral issues, such as water supplies, forests, and flooding, and evaluate options for action. Many adaptation actions will have not only economic implications but will affect other environmental issues. "We shouldn't try to think of some of these adaptation responses as just dealing with climate risk," he said.

On contentious issues, the Academy could serve as a "referee," Casola continued, bringing the best scientific information and analysis to a topic. An example would be the impacts of a carbon tax or a cap-and-trade system in reducing emissions and their distributional impacts on state residents. Another example, cited by Leung, involves the attribution of trends and events to climate change. This can be a difficult and counterintuitive undertaking, noted Mass. For example, one of the worst weather-related hazards in Washington State is black ice that forms on roadways on cold winter days. If climate change reduces the number of such days, the number of accidents caused by black ice will decrease.

Mass also emphasized the importance of remaining politically neutral and not being seen as an advocate for particular social objectives. "That's the fine line we need to find."

Coordinating Across Sectors

Several presenters pointed out that issues related to climate tend to be siloed across state agencies, research organizations, and educational institutions. Yet the issues raised by climate change span disciplines, sectors, and levels of government. As Winton pointed out, the floods produced by heavier precipitation events interact with agriculture and fisheries, which interact with treaties with Native American groups. As a specific action item, he suggested that the Academy encourage regional, multiagency, and multistate approaches for watershed management to include anticipated effects of climate change on fish and other aquatic species. As an example of the complex issues involved, he mentioned the effects of dams on fish runs. If the lower river dams were removed, would upper river dams be needed to provide cold water and flows for fish at critical times of the year? "Do we have dams in the wrong places, or do we not want dams at all? That's an issue that would be worth discussing."

Casola emphasized that special attention should be given to governance roles among state, county, and local entities. Some governmental entities, such as King County and the City of Seattle, are ahead on certain issues, and other entities could take advantage of their experience. He also pointed toward the need for the state to connect with local health agencies, which do not have the resources to tackle the problems they face.

The Academy could identify and help to overcome the barriers to integrated approaches. For example, Ebi noted that privacy restrictions can make it difficult to access the data needed to attribute health effects to climate change. Studying the health consequences of climate change also requires long-term support, she said, which can be difficult for people working in public health on short-term grants.

As a multidisciplinary scientific organization, the Academy has the resources to synthesize information on climate change across temporal and spatial scales. It could provide technical assistance and advice that would be useful for decision makers at all levels of the public and private sectors.

Education and Outreach

Finally, several presenters observed that the Academy could intensify its work on education and outreach. Other organizations have been studying how best to communicate the scientific substance of the issues associated with climate change, and the Academy could build on and contribute to this work. As Ebi noted, "there's a whole field that's working on communication — increasing capacity, increasing awareness, and increasing understanding." Citing a specific example, Bond suggested working with the Washington chapter of Physicians for Social Responsibility, which is increasing its outreach work on climate change issues.

Winton recommended placing students in fellowship positions in state agencies or nongovernmental organizations to provide a scientific grounding for the work going on in those organizations. He also suggested that the Academy could assist in outreach efforts to make the public aware of future impacts of climate change on fish and other aquatic organisms.

Conversations with stakeholders are critical, said Mass. "I gave a talk at the Rotary Club in Yakima, and if you think these people didn't care about global warming, you're wrong. They are worried about it. They want more reservoirs to store the water. These are the kinds of conversations we need to have in the state."

Appendix A

WASHINGTON STATE
Academy of Sciences

10TH ANNUAL MEETING & SYMPOSIUM
September 14, 2017 | Museum of Flight, Seattle, WA

CLIMATE CHANGE IN WASHINGTON STATE
Research Questions Critical to Preparing for the Future

SYMPOSIUM AGENDA

Synopsis: *Washington State is among the leading states in understanding and actively preparing for the effects of climate change. Researchers across the region have investigated the current and future climate risks that face natural resources, human well-being, and the economy of the state. The State is a leader in pursuing actions to reduce greenhouse gas emissions. State agencies and some counties and other local jurisdictions are out front in developing plans to prepare for future climate conditions in order to minimize the negative effects of climate change. However, research questions remain regarding future climate impacts and additional research needed to document the degree and scale of the effectiveness of actions now being taken.*

Symposium Introduction

12:30 – 12:40 **Introduction** – *Anjan Bose, President and Ron Thom, President Elect*

Climate History and Predicting Climate Change

12:40 - 1:00 **Changes in the climate of Washington State over the past century** – *Nick Bond (UW, State of Washington Climatologist)*

1:00 – 1:20 **Regional climate modeling technology: Initial results, Regional Climate Modeling Consortium** – *Cliff Mass (UW and WSAS member)*

1:20 – 1:40 **Projecting regional climate change: approaches, uncertainties, and extreme events** – *Ruby Leung (PNNL and WSAS member)*

Climate Change Impacts I

1:40 - 2:00 **Hydrology, water resources and agriculture** – *Jennifer Adam (WSU)*

2:00 - 2:20 **Climate change impacts on energy systems, focusing on integrated multi-scale modeling** – *Ian Kraucunas (PNNL)*

2:20 – 2:40 **Human health** – *Kristie Ebi (UW)*

2:40 – 3:00 **Economics of adaptation** – *Jonathan Yoder (WSU and WSAS Member)*

3:00 – 3:20 **Break**

Climate Change Impacts II

3:20 – 3:40 **Ocean acidification** – *Terrie Klinger (UW)*

3:40 – 4:00 **The impact of climate change on diseases of fish** – *James Winton (USGS Emeritus)*

4:00 – 4:20 **Puget Sound ecosystem recovery** – *John Stein (NOAA-NWFSC (retired); Chair Puget Sound Partnership Science Advisory Committee)*

Summary

4:20 – 4:45 **How is Washington preparing?** – *Joe Casola (Deputy Director, Climate Impacts Group, UW)*

Discussion and Next Steps for WSAS

4:45 – 5:45 **Facilitated discussion**

PAGE LEFT
INTENTIONALLY BLANK

Appendix B

WASHINGTON STATE
Academy of Sciences
10TH ANNUAL MEETING & SYMPOSIUM
September 14, 2017 | Museum of Flight, Seattle, WA
CLIMATE CHANGE IN WASHINGTON STATE
Research Questions Critical to Preparing for the Future

SYMPOSIUM SPEAKERS Page 1 of 4

Nick Bond, *Changes in the climate of Washington State over the past century*

Dr. Nick Bond is a principal research scientist with the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) of the University of Washington (UW), and is affiliated with the Pacific Marine Environmental Laboratory (PMEL) of NOAA. He has been the State Climatologist for Washington since 2010. He has a Ph.D. in Atmospheric Sciences from the University of Washington. His research is on a broad range of topics with a focus on the weather and climate of the Pacific Northwest and the linkages between the climate and marine ecosystems of the North Pacific. Much of his recent attention has been on the causes and effects of the marine heat wave of 2014-16 in the NE Pacific Ocean. He cheerfully acknowledges being a weather geek.

Cliff Mass, *Regional climate modeling technology: Initial results, Regional Climate Modeling Consortium*

Dr. Cliff Mass, a full professor at the UW, is a fellow of the American Meteorological Society, has been an editor of a number of meteorological journals, is a member of the Washington State Academy of Sciences, and has served as a member of a number of National Academy committees. He is currently a member of the WRF Research Applications Board, a member of the NOAA/UCAR UMAC committee, and a member of several American Meteorological Society committees. He is now working on a new book "The Secrets of Weather Prediction."

He and his students have systematically studied the weather and climate of the western U.S., completing over seventy papers on West Coast phenomena as varied as orographic precipitation, coastal surges, the Catalina Eddy, and the Puget Sound convergence zone, to onshore pushes, downslope windstorms, and various local gap winds. Numerical simulation has been a key tool for his group, which now runs the most extensive local high-resolution prediction system in the United States. He is also heavily involved in regional climate modeling for the western U.S.

Dr. Mass has been involved in a number of other initiatives, including the acquisition of coastal radar on the Washington coast, improving the infrastructure of the National Weather Service, the use of smartphone pressure observations for weather prediction, and the improvement of K-12 math education. He is the author of the 2008 book "The Weather of the Pacific Northwest" and broadcasts a weekly weather information segment on KNKX, a local public radio station. Dr. Mass also writes a weather blog (cliffmass.blogspot.com)

Ruby Leung, *Projecting regional climate change: approaches, uncertainties, and extreme events*

Dr. L. Ruby Leung is a Battelle Fellow at PNNL and an Affiliate Scientist at National Center for Atmospheric Research. Her research broadly cuts across multiple areas in modeling and analysis of climate and water cycle including orographic processes, monsoon climate, climate extremes, land surface processes, land-atmosphere interactions, and aerosol-cloud interactions. She is the Chief Scientist of Energy Exascale Earth System Model (E3SM) supported by the Department of Energy. She has been actively involved in development and application of regional climate models as well as evaluation and analysis of high resolution and variable resolution global climate models. She has served on advisory panels and National Research Council committee that define future priorities in climate modeling. Dr. Leung is an elected member of the National Academy of Engineering. She is also a fellow of the American Association for the Advancement of Science (AAAS), American Geophysical Union (AGU), and American Meteorological Society (AMS). She received a BS in Physics and Statistics from Chinese University of Hong Kong and an MS and PhD in Atmospheric Sciences from Texas A&M University. She has published over 240 peer-reviewed journal articles.

Jennifer Adam, *Hydrology, water resources and agriculture*

Dr. Jennifer Adam is Associate Professor of Civil Engineering at Washington State University and also Associate Director of the State of Washington Water Research Center. She received her graduate degrees at the University of Washington and her undergraduate degree at the University of Colorado Boulder, all in Civil and Environmental Engineering. Dr. Adam is interested in the connections between climate, hydrology, land use, and ecological (natural and agricultural) processes. This includes understanding how climate variations and direct human influences interact to alter land surface hydrologic processes at watershed, regional, and global scales. Her research group applies process-based models in integrated modeling frameworks to explore these interactions. She is lead investigator on several large projects, including the Washington State Water Supply and Demand Forecast and an NSF project investigating the food-energy-water nexus in the Columbia River basin.

Ian Kraucunas, *Climate change impacts on energy systems, focusing on integrated multi-scale modeling*

Dr. Ian Kraucunas is the director of the Atmospheric Sciences and Global Change Division at Pacific Northwest National Laboratory. The division has over 140 staff with expertise ranging from fundamental atmospheric physics to regional and global climate modeling to integrated assessment and climate impact analysis. He also serves as principal investigator for the "Integrated Multi-sector, Multi-scale Modeling (IM^3)" scientific focus area, a multi-institution Department of Energy project focused on developing and applying integrated modeling platforms that can simulate the complex interactions among climate, energy, water, land, and other human and natural systems. Prior to joining PNNL, Dr. Kraucunas was a senior program officer with the Board on Atmospheric Sciences and Climate at the National Research Council of the National Academy of Sciences, where he led a number of projects and repots related to climate and global change research. Dr. Kraucunas received a Ph.D. and M.S. in Atmospheric Sciences from the University of Washington, Seattle, and a B.A. in Physics and Environmental Science from the University of Virginia.

Kristie Ebi, *Human health*

Dr. Kristie L. Ebi is director of the Center for Health and the Global Environment (CHanGE), and Rohm and Haas Endowed Professor in Public Health Sciences at the University of Washington. She has been conducting research and practice on the health risks of climate variability and change for twenty years, including on extreme events, thermal stress, foodborne safety and security, and vectorborne diseases. She focuses on understanding sources of vulnerability, estimating current and future health risks of climate change, and designing adaptation policies and measures to reduce the risks of climate change in multi-stressor environments. She has supported multiple countries in Central America, Europe, Africa, Asia, and the Pacific in assessing their vulnerability and implementing adaptation measures. She also co-chairs the International Committee On New Integrated Climate change assessment Scenarios (ICONICS), facilitating development of new climate change scenarios. Dr. Ebi's scientific training includes an M.S. in toxicology and a Ph.D. and a Masters of Public Health in epidemiology, and two years of postgraduate research at the London School of Hygiene and Tropical Medicine. She has edited fours books on aspects of climate change and has more than 200 publications.

Jonathan Yoder, *Economics of adaptation*

Dr. Jonathan Yoder is a Professor in the School of Economic Sciences at Washington State University, Director of the State of Washington Water Research Center, and Affiliate Faculty in the Paul G. Allen School for Global Animal Health at Washington State University. He is an environmental and natural resource economist specializing in water law and economics, climate and energy policy, health and economic development in low-income communities, among other topics.

Dr. Yoder is on the Board of Directors for the Universities Council on Water Resources (UCOWR), and was recently on the Expert Council on Climate and Environmental Change for the Washington State Department of Natural Resources. He is also on the Editorial Board of the Journal of Water Economics and Policy and the Journal of Contemporary Water Research and Education, among several past editorial positions. Along with collaborators and students, he has been the recipient of several quality of research awards.

Dr. Yoder holds a B.A. in Biology and Journalism from Indiana University, a M.S. in Applied Economics from Montana State University, and a PhD in Economics from North Carolina State University.

Terrie Klinger, *Ocean acidification*

Dr. Terrie Klinger is Director of the School of Marine and Environmental Affairs, Co-Director of the Washington Ocean Acidification Center, and holds the Stan and Alta Barer Endowed Professorship in Sustainability Science in honor of Dr. Edward Miles. Trained as a marine ecologist, she studies ecosystem-based approaches to managing natural resources in the ocean, the ecological effects of environmental stressors such as habitat loss and ocean acidification, and how rocky intertidal communities respond to and recover from disturbance. She leads a graduate training program focused on ocean change and its consequences for the human communities connected to them. The Pacific Northwest and the Gulf of Alaska are her primary study areas. She obtained her Ph.D. in Biological Oceanography from Scripps Institution of Oceanography.

James Winton, *The impact of climate change on diseases of fish*

Dr. Jim Winton is a Senior Scientist, Emeritus, in the Fish Health Research Section at the USGS Western Fisheries Research Center in Seattle, Washington where he collaborates with a team of scientists, technicians, post-doctoral researchers, graduate students and visiting scientists working to improve the detection of fish pathogens, determine factors controlling the epidemiology of fish diseases, and develop control strategies for reducing losses among both hatchery and wild fish. Jim is also an Affiliate Professor in the School of Aquatic and Fishery Sciences at the University of Washington where he serves on departmental or graduate student committees and gives an occasional seminar or lecture. He has served as: President of the Fish Health Section of the American Fisheries Society, member of the Editorial Boards of the Journal of Aquatic Animal Health, Diseases of Aquatic Organisms, Journal of Fish Diseases, and Journal of Applied Ichthyology, and member of the International Committee on Taxonomy of Viruses, the American Type Culture Collection, the USDA Aquaculture Technical and Scientific Committee, and the Fish Disease Commission of the World Organization for Animal Health. Significant awards include the American Fisheries Society Fish Health Section S. F. Snieszko Distinguished Service Award and the US Department of the Interior Distinguished Service Award. He is an author of more than 200 scientific publications.

SYMPOSIUM SPEAKERS Page 4 of 4

John Stein, *Puget Sound ecosystem recovery*

Dr. John Stein is the former Science and Research Director of NOAA Fisheries' Northwest Fisheries Science Center in Seattle, WA, and is currently Scientist Emeritus with NOAA Fisheries. The Center's scientific responsibilities are for living marine resources (e.g., salmon, groundfish, and killer whales) and their habitats of the Pacific Northwest (e.g., salmon) and along the west coast (e.g., groundfish). He has authored over 75 publications, is an affiliate faculty member in the University of Washington's School of Aquatic and Fisheries Sciences, and is currently the Vice-Chair of PICES (North Pacific Marine Science Organization) a multinational organization of Pacific Rim countries. At NOAA, in addition to his duties as Science Center Director he co-directed NOAA Fisheries California Current Integrated Ecosystem Assessment with the director of the SW Fisheries Science, and was the federal co-lead for Marine Planning on the west coast under the National Ocean Policy. Currently he serves as the Chair of the Puget Sound Partnerships Science Panel and is on the board of the Skagit Watershed Council.

Joe Casola, *How is Washington preparing?*

Dr. Joe Casola is the Deputy Director at the UW Climate Impacts Group. Dr. Casola has worked on issues related to climate science and policy for more than 15 years. His career has focused on translating information about climate variability, climate change, and climate impacts for policymakers, resource managers, and business leaders. He previously served as Staff Scientist and Program Director for Science and Impacts at the Center for Climate and Energy Solutions (C2ES) in Washington, DC; a Senior Associate at ICF International; and a Post-Doctoral Fellow at the National Research Council. Casola earned his Ph.D. and M.S. degrees in Atmospheric Sciences from the University of Washington, where his research examined the response of snowpack in the Cascades to rising temperatures. He also holds a B.S. in Chemistry from Duke University.

Additional Reading

Abatzoglou, J. T., D. E. Rupp, and P. W. Mote. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. *Journal of Climate* 27:2125-2142. Available at http://webpages.uidaho.edu/jabatzoglou/PDF/Abatzoglouetal2014.pdf.

Binder, L., J. Barcelos, D. Booth, M. Darzen, M. Elsner, R. Fenske, T. Graham, A. Hamlet, J. Hodges-Howell, J. Jackson, C. Karr, P. Keys, J. Littell, N. Mantua, J. Marlow, D. McKenzie, M. Robinson-Dorn, E. Rosenberg, C. Stöckle, and J. Vano. 2010. Preparing for climate change in Washington State. *Climatic Change* 102(1):351-376.

Bumbaco, K. A., K. D. Dello and N. A. Bond. 2013: History of Pacific Northwest heat waves: Synoptic pattern and trends. *Journal of Applied Meteorology and Climatology* 52:1618-1631.

Burge, C. A., C. M. Eakin, C. S. Friedman, B. Froelich, P. K. Hershberger, E. E. Hofmann, L. E. Petes, K. C. Prager, E. Weil, B. L. Willis, S. E. Ford, and C. D. Harvell. 2014. Climate change influences on marine infectious diseases: implications for management and society. *Annual Review of Marine Science* 6:249-277.

Climate Impacts Group. 2009. *The Washington Climate Change Impacts Assessment*. M. McGuire Elsner, J. Littell, and L. Whitely Binder, eds. Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. Available at: http://www.cses.washington.edu/db/pdf/wacciareport681.pdf.

Dalton, M. M., P. W. Mote, and A. K. Snover, eds. 2013. *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities.* Washington, DC: Island Press. Available at http://cses.washington.edu/db/pdf/daltonetal678.pdf.

Department of Ecology, State of Washington. 2012. *Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy*. Publication No. 12-01-004. Olympia, WA: Washington State Department of Ecology. Available at www.ecy.wa.gov/biblio/1201004.html.

Ebi, K. L., N. H. Ogen, J. C. Semenza, and A. Woodward. 2017. Detecting and attributing health burdens to climate change. *Environmental Health Perspectives* 125(8):085004-1-098004-8.

Elsner, M. M., L. Cuo, N. Voisin, J. Deems, A. F. Hamlet, J. A. Vano, K. E. B. Mickelson, S. Y. Lee, and D. P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* 102(1-2):225-260.

Gao, Y., J. Lu, L. R. Leung, Q. Yang, S. Hagos, and Y. Qian. 2015. Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophysical Research Letters* 42:7179–7186.

Hall, S. A., J. C. Adam, M. Barik, J. Yoder, M. P. Brady, D. Haller, M. E. Barber, C. E. Kruger, G. G. Yorgey, M. Downes, C. O. Stockle, B. Aryal, T. Carlson, G. Damiano, S. Dhungel, C. Einberger, K. Hamel-Reiken, M. Liu, K. Malek, S. McClure, R. Nelson, M. O'Brien, J. Padowski, K. Rajagopalan, Z. Rakib, B. Rushi, and W. Valdez. 2016. *Columbia River Basin Long-Term Water Supply and Demand Forecast*. Publication No. 16-12-001. Washington Department of Ecology, Olympia, WA. Available at https://fortress.wa.gov/ecy/publications/documents/1612001.pdf or http://www.ecy.wa.gov/programs/wr/cwp/2016Forecast.html.

Hamlet, A. F., S. Y. Lee, K. E. B. Mickelson, and M. M. Elsner. 2010. Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. *Climatic Change*

102(1-2):103-128.

Hamlet, A. F., P. Carrasco, J. Deems, M. M. Elsner, T. Kamstra, C. Lee, S-Y Lee, G. Mauger, E. P. Salathe, I. Tohver, and L. Whitely Binder. 2010. *Final Project Report for the Columbia Basin Climate Change Scenarios Project*. Available at http://www.hydro.washington.edu/2860/report.

Hsiang, S., R. Kopp, A. Jina, H. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser. 2017. Estimating economic damage from climate change in the United States. *Science* 356(6345):1362-1369.

Isaksen, T. B., M. G. Yost, E. K. Hom, Y. Ren, H. Lyons, and R. A. Fenske. 2015. Increased hospital admissions associated with extreme-heat exposure in King County, Washington, 1990-2010. *Reviews on Environmental Health* 30(1):51-64.

Jackson, J. E., M. G. Yost, C. Karr, C. Fitzpatrick, B. Lamb, S. H. Chung, J. Chen, J. Avise, R. A. Rosenblatt, and R. A. Fenske. 2010. Public health impacts of climate change in Washington State: Projected mortality risks due to heat events and air pollution. *Climatic Change* 102(1-2):159-186.

Kraucunas, I., L. Clarke, J. Dirks, J. Hathaway, M. Hejazi, K. Hibbard, M. Huang, C. Jin, M. Kintner-Meyer, K. Kleese van Dam, R. Leung, H.-Y. Li, R. Moss, M. Peterson, J. Rice, M. Scott, A. Thomson, N. Voisin, and T. West. 2014. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: The Platform for Regional Integrated Modeling and Analysis (PRIMA). *Climatic Change* 129(3-4):573-588.

Leung, L. R., T. Ringler, W. D. Collins, M. Taylor, and M. Ashfaq. 2013. A hierarchical evaluation of regional climate simulations. *Eos Transactions* 94(34):297-298.

Littell, J. S., M. M. Elsner, L. C. Whitely Binder, and A. K. Snover, eds. 2009. *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Climate Impacts Group, University of Washington, Seattle, WA.

Littell, J. S., E. E. Oneil, D. McKenzie, J. A. Hicke, J. A. Lutz, R. A. Norheim, and M. M. Elsner. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change* 102(1-2):129-158.

Mantua, N. J., I. Tohver, and A. F. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102(1-2):187-223.

Marcogliese, D. J. 2008. The impact of climate change on the parasites and diseases of aquatic animals. World Organization for Animal Health (OIE) *Scientific and Technical Review* 27(2):467-484.

Mauger, G. S., J. H. Casola, H. A. Morgan, R. L. Strauch, B. Jones, B. Curry, T. M. Busch, L. Whitely Binder, M. B. Krosby, and A. K. Snover. 2015. *State of Knowledge: Climate Change in Puget Sound.* Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. Available at http://cses.washington.edu/picea/mauger/ps-sok/PS-SoK_2015.pdf.

McLaughlin, J. B., A. DePaola, C. A. Bopp, K. A. Martinek, N. P. Napolilli, C. G. Allison, S. L. Murray, E. C. Thompson, M. M. Bird, and J. P. Middaugh. 2005. Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New England Journal of Medicine* 353:1463-1470.

Miles, E., M. Elsner, J. Littell, L. Binder, and D. Lettenmaier. 2010. Assessing regional impacts and adaptation strategies for climate change: the Washington Climate Change Impacts Assessment. *Climatic Change* 102(1-2):9-27.

Monaghan, A. J., C. W. Morin, D. F. Steinhoff, O. Wilhelmi, M. Hayden, D. A. Quattrochi, M. Reiskind, A. L. Lloyd, K. Smith, C. A. Schmidt, P. E. Scalf, and K. Ernst. 2016. On the seasonal occurrence and abundance of the Zika virus vector mosquito Aedes Aegypt in the contiguous United States. *PLOS Currents Outbreaks* 1:1-33.

Montag, J., K. Swan, K. Jenni, T. Nieman, J. Hatten, M. Mesa, D. Graves, F. Voss, M. Mastin, J. Hardiman, and A. Maule. 2014. Climate change and Yakama National tribal well-being. *Climatic Change* 124(1-2):385-398.

Mote, P. W., and E. P. Salathé. 2010. Future climate in the Pacific Northwest. *Climatic Change* 102(1-2):29-50.

National Marine Fisheries Service. 2016. *2015 Adult Sockeye Salmon Passage Report*. Available at http://www.westcoast.fisheries.noaa.gov/publications/hydropower/fcrps/2015_adult_sockeye_salmon_passage_report.pdf.

Partridge, C., and B. McGregor. 2007. *The Future of Washington Forests*. Washington Department of Natural Resources, Olympia, WA.

Raymond, C. L., D. L. Peterson, and R. M. Rochefort. 2014. Climate change vulnerability and adaptation in the North Cascades Region, Washington. General Technical Report, PNW-GTR-892. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Available at https://doi.org/10.2737/PNW-GTR-892.

Sakaguchi, K., L. R. Leung, C. Zhao, Q. Yang, J. Lu, S. Hagos, T. D. Ringler, S. A. Rauscher, and L. Dong. 2015. Exploring a multi-resolution approach using AMIP simulations. *Journal of Climate* 28(14):5549-5574.

Sakaguchi, K., J. Lu, L. R. Leung, C. Zhao, Y. Li, and S. Hagos. 2016. Sources and pathways of the upscale effects on the southern hemisphere jets in MPAS-CAM4 variable resolution simulations. *Journal of Advances in Modeling Earth Systems* 8(4):1786-1805.

Salathé, E. P., L. R. Leung, Y. Qian, and Y. Zhang. 2010. Regional climate model projections for the State of Washington. *Climatic Change* 102(1-2):51-75.

Saperstein, A. 2015. *Climate Change, Migration, and the Puget Sound Region: What We Know and How We Could Learn More.* Report prepared for the University of Washington Climate Impacts Group. The Daniel J. Evans School of Public Policy and Governance, University of Washington, Seattle. Available at https://cig.uw.edu/wp-content/uploads/sites/2/2015/10/Climate-Migration-Saperstein-Final-Aug-3-2015.pdf.

Siemann, D., and L. W. Binder. 2017. *Preliminary Climate Change Assessment for Puget Sound Partnership*. A Collaboration of Puget Sound Partnership and the University of Washington Climate Impacts Group. Seattle, WA. Available at https://cig.uw.edu/wp-content/uploads/sites/2/2017/08/Preliminary-Climate-Assessment-for-PS-Partnership-FINAL.pdf.

Snover, A. K., G. S. Mauger, L. C. Whitely Binder, M. Krosby, and I. Tohver. 2013. *Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers.* State of Knowledge Report prepared for the Washington State Department of Ecology. Climate Impacts Group, University of Washington, Seattle. Available at http://cses.washington.edu/db/pdf/snoveretalsok816.pdf.

Stöckle, C., R. L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, and C. Kruger. 2010. Assessment of climate change impact on eastern Washington agriculture. *Climatic Change* 102(1-2):77-102.

Tornevi, A., L. Barregárd, and B. Forsberg. 2015. Precipitation and primary health care visits for gastrointestinal illness in Gothenburg, Sweden. *PLoS ONE* 10(5):e0128487.

Voisin, N., M. Kintner-Meyer, R. Skaggs, T. Nguyen, D. Wu, J. Dirks, Y. Xie, and M. Hejazi 2016. Vulnerability of the US western electric grid to hydro-climatological conditions: How bad can it get? *Energy* 115:1-12.

Whiteley Binder, L. C., and J. Jurjevich. 2016. *The Winds of Change? Exploring Climate Change-driven Migration and Related Impacts in the Pacific Northwest: Symposium Summary.* Portland State University Population Research Center (Portland, Oregon) and the University of Washington Climate Impacts Group (Seattle, Washington). Available at https://cig.uw.edu/wp-content/uploads/sites/2/2014/11/climate-migration-symposium-summary.pdf.

Whitely Binder, L. C., H. Morgan, and D. Siemann. 2017. *Preparing Washington State Parks for Climate Impacts: A Climate Change Vulnerability Assessment for Washington State Parks.* A collaboration of the Washington State Parks and Recreation Commission and the University of Washington Climate Impacts Group. Seattle, WA. Available at http://dx.doi.org/10.3955/046.090.0106.

Wimberly, M. C., and Z. Liu. 2014. Interactions of climate, fire, and management in future forests of the Pacific Northwest. *Forest Ecology and Management* 327:270-279.

WASHINGTON STATE

Academy of Sciences

Washington State Academy of Sciences
901 5th Avenue, Suite 2900
Seattle, WA 98164
wsas.programs@washacad.org
www.washacad.org
(206) 219-2401