PNNL-33801

# Exploring Multiscale Earth System and Human-Earth System Dynamics in the Puget Sound Region

Scoping Study Report

January 2023

Nathalie Voisin
Debbie Rose
Dan Broman
Ning Sun
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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# Summary

With its mountain-to-coast hydroclimate, strong influence of Pacific Ocean weather systems and climate patterns, and unique land use history with strong rural-to-urban gradients, the Puget Sound region is a natural laboratory for studying a number of complex processes in, and interactions among, different Earth and human systems. A 1-year scoping study was initiated by the Earth and Environmental Systems Modeling program of the Department of Energy's Office of Science Biological and Environmental Research. It was intended to elucidate and highlight the rich opportunities Puget Sound offers to advance our understanding of and ability to simulate Earth system changes and human-Earth system interactions. A literature review, multi-day community workshop, and external input were used to develop this scoping study report.

The report first summarizes scientific understanding and knowledge gaps associated with major regional systems, including atmosphere and climate, the land surface, coastal and marine processes, and human systems, as well as how these systems are changing over time. It then highlights some of the most notable extreme events in the region, including heat waves, atmospheric rivers, droughts, and wildfires. Finally, key research opportunities for Earth and environmental systems modeling in, above, and around Puget Sound are highlighted.

# Acknowledgments

The work reported here would not have been possible without the support and leadership of the U.S. Department of Energy, in particular Gary Geernaert, Xujing Davis, Renu Joseph, and Bob Vallario for setting the context of the workshop and guiding discussions.

We are extremely grateful for the leadership of our scientific steering committee in designing, organizing, and facilitating the workshop and for their contributions to and review of this report:

- Bart Nijssen, Civil and Environmental Engineering, University of Washington
- Chris Nolte, Environmental Protection Agency
- David Judi, Pacific Northwest National Laboratory
- Guillaume Mauger, Climate Impact Group, University of Washington
- Jeff Arnold, the MITRE Corporation
- Lynn McMurdie, Atmospheric Sciences, University of Washington
- Ruby Leung, Pacific Northwest National Laboratory
- Simone Alin, National Oceanic and Atmospheric Administration.

We also acknowledge our guest speakers at the workshop for their engaging presentations: Flavio Lehner (Cornell University), Nick Bond (Washington State Climatologist), Marina Alberti (University of Washington), Ronda Strauch (Seattle City Light), and Ruby Leung. Lastly, we thank all of those who attended and participated in the workshop for sharing their ideas and expertise, as well as the following additional reviewers: Xiaodong Chen, Andre Coleman, Samson Hagos, Brian O'Neill, Yun Qian, Vince Tidwell, Nicholas Ward, Mark Wigmosta, Zhaoqing Yang, and Jim Yoon.

## Acronyms and Abbreviations

| | |
|---|---|
| AI | artificial intelligence |
| AR | atmospheric river |
| BER | Biological and Environmental Research |
| COMPASS | Coastal Observations Mechanisms and Predictions Across Systems and Scales |
| DOE | Department of Energy |
| E3SM | Energy Exascale Earth System Model |
| EESM | Earth and Environmental Systems Modeling |
| ENSO | El Niño Southern Oscillation |
| ESM | Earth system model |
| ESMD | Earth System Model Development |
| GCM | global climate model |
| HRCD | high-resolution change detection |
| ICoM | Integrated Coastal Modeling |
| IVT | Integrated Vapor Transport |
| ML | machine learning |
| MSD | multisector dynamics |
| NWIFC | Northwest Indian Fisheries Commission |
| NWPCC | Northwest Power and Conservation Council |
| PDO | Pacific Decadal Oscillation |
| RCP | Representative Concentration Pathway |
| RGMA | Regional and Global Modeling Analysis |
| ROS | rain-on-snow |
| SST | sea-surface temperature |
| SWE | snow water equivalent |
| U.S. | United States |
| USGS | United States Geological Service |

# Contents

# Figures

# 1.0 Introduction

The Puget Sound region is located near the northwest corner of the contiguous United States in the state of Washington and has a shoreline of more than 2,500 miles. Puget Sound is the second largest estuary in the United States, with a drainage area of about 30,000 km$^2$ (Figure 1), and is part of the larger Salish Sea, which also includes the Canadian waters in the Strait of Georgia as well as the Strait of Juan de Fuca. The region is characterized by complex terrain, with the Olympic and Cascade mountain ranges straddling a highly populated coastal plain (Figure 2), and features diverse land covers ranging from densely forested uplands to highly urbanized lowlands. It is home to a rich and diverse set of terrestrial, aquatic, and coastal ecosystems ranging from alpine glaciers to rich shellfish beds to some of the most productive conifer forests in the world (Quinn 2010). The Puget Sound region supports a population approaching five million people, including 29 Native American tribes. The region is a major hub for fishing, forestry, technology, and trade, and its hydroclimate, ecological, transportation, communication, and energy systems are strongly influenced by the region's climate, geography, and topography, as well as by connections to other West Coast states and international waters.

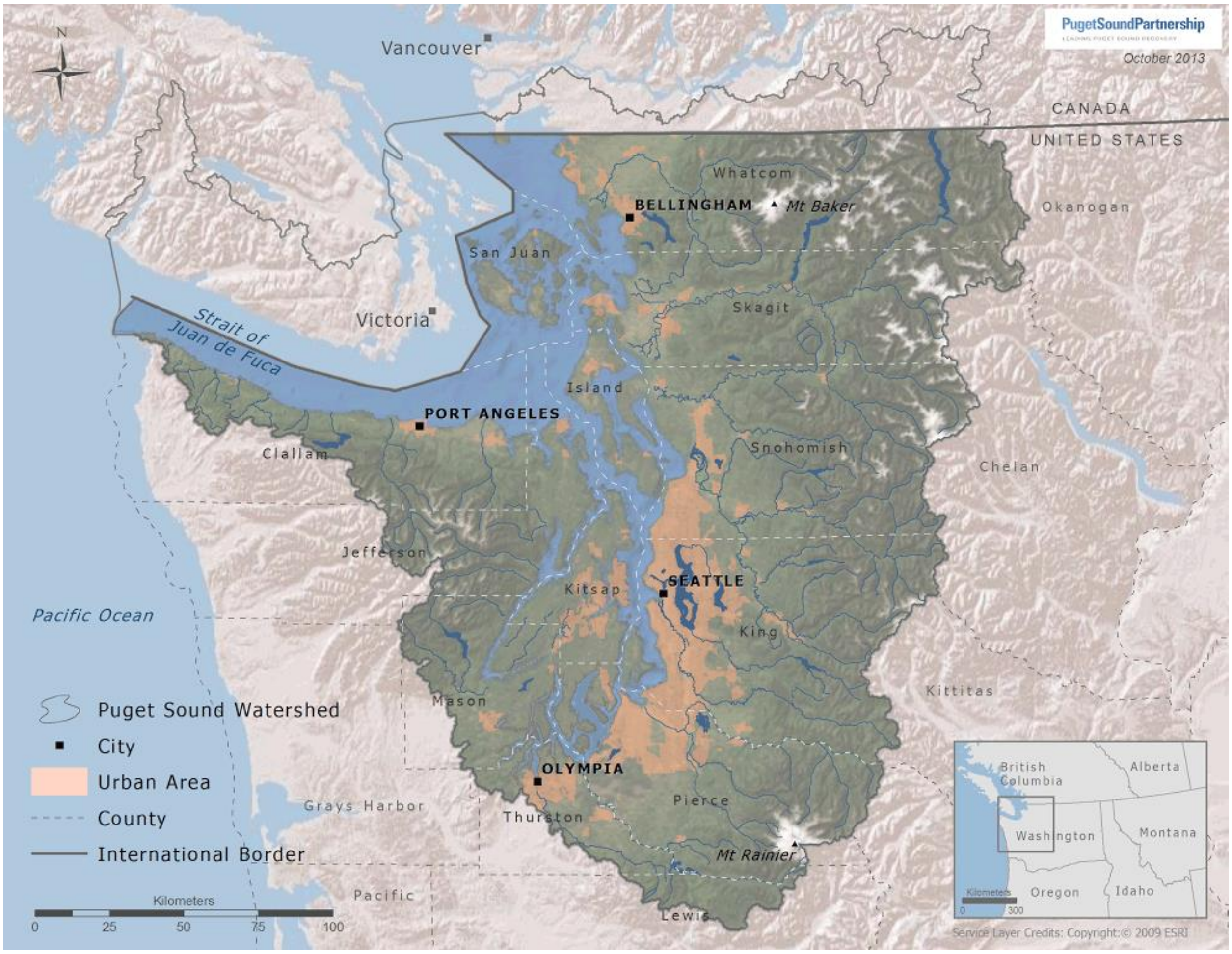


Figure 1. Puget Sound watershed boundary (Source: Puget Sound Partnership).

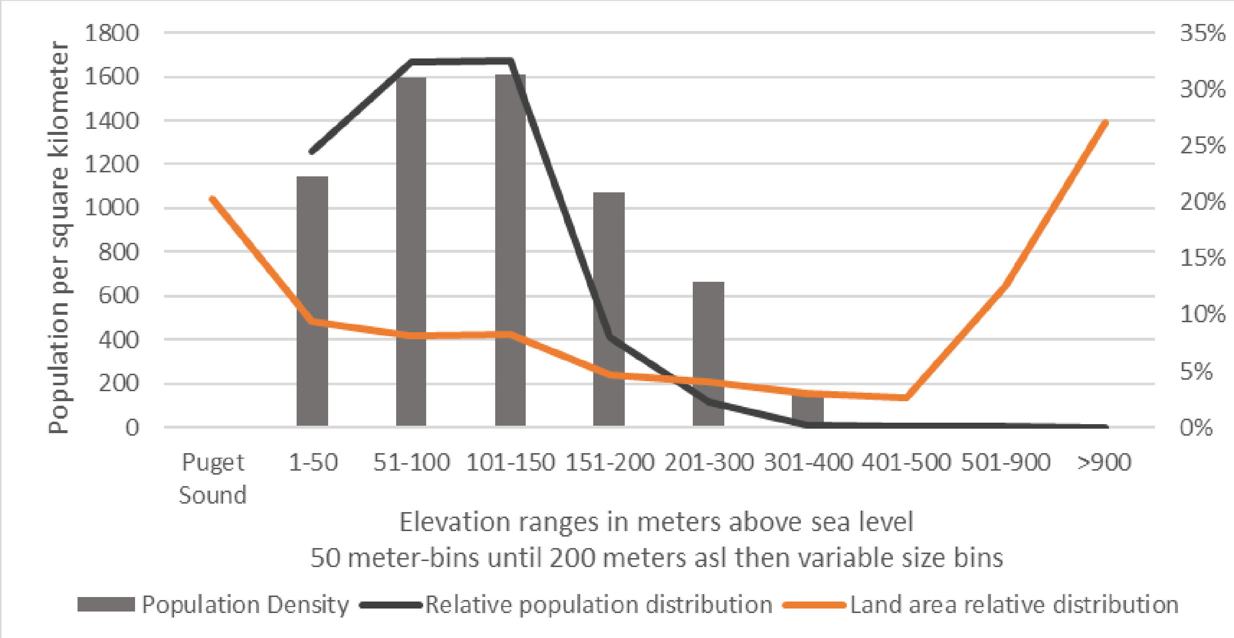


Figure 2. Population density, relative population distribution, and relative land area distribution across different elevation bins in the Puget Sound region. Based on data from the 2020 United States Census and USGS National Elevation Dataset.

With its mountain-to-coast hydroclimate, strong influence of Pacific Ocean weather systems and climate patterns, and complex land use history with strong rural-urban gradients, the Puget Sound region is a natural laboratory for studying the complex interactions among human and Earth systems. Water is a particularly important resource that connects many systems across the region, including hydropower generation, the transport of sediment and pollutants, aquatic and marine ecosystem dynamics, shipping, and commercial and recreational activities. The Puget Sound region (along with the broader Pacific Northwest) is experiencing a wide range of long-term stresses such as changing atmospheric circulation patterns, sea level changes, declining snowpack, glacial retreat, population growth, aging infrastructure, and land use and land cover changes characterized by substantial logging and urbanization. The region also experiences high-impact extreme events, many of which are increasing in frequency or intensity, including AR, floods, droughts, wildfires, and heat waves.

The Puget Sound region is also quite geologically active. A number of faults crisscross the region and several major earthquakes have struck over the past several decades, including the magnitude 6.8 Nisqually earthquake in 2001. Even larger megathrust earthquakes originating at the Cascadia subduction zone in the Pacific Ocean are capable of producing earthquakes exceeding magnitude 9 and triggering large tsunamis (see, e.g., Garrison-Laney and Miller 2017). The region is also well known for its volcanoes, especially Mount Saint Helens, which erupted explosively in 1980, and Mount Rainier, which some consider the most dangerous volcano in North America (Scott et al. 1995). Land areas in the highly populated Puget Sound lowlands are dominated by glacial sediments, and the steep shoreline common across Puget Sound are prone to landslides (Karlin et al. 2004; Smith 2012). These geological threats are notable because they mean the region has experience in preparing for and responding to extreme events, and some of the preparedness and adaptation measures (e.g., reducing shoreline vulnerability and landslide risks) associated with these geologic risks could be synergistic with efforts to reduce vulnerability to climate change and extreme weather events.

## 1.1 Purpose and Scope

To elucidate and highlight the rich opportunities that the Puget Sound region offers to advance our understanding of and ability to simulate Earth system changes and human-Earth system interactions, a 1-year scoping and pilot study was initiated in fall 2021 by the Earth and Environmental Systems Modeling (EESM) program of the Department of Energy's (DOE's) Office of Science Biological and Environmental Research (BER). DOE-BER is currently investing in major coastal research efforts in the mid-Atlantic, Great Lakes regions through the Integrated Coastal Modeling (ICoM), Coastal Observations, Mechanisms, and Predictions Across Systems and Scales (COMPASS), and Interdisciplinary Research for Arctic Coastal Environments (InteRFACE) projects, respectively, along with a number of additional synergistic efforts focusing on specific coastal processes and domains. DOE has also defined an even broader set of coastal research priorities (DOE 2017) and worked as part of an interagency team to define broader priorities for coastal modeling (USGCRP 2020). The Puget Sound region offers a unique context to further advance our understanding of coastal systems, with its West Coast climate regime, sharp topographic gradients, and unique ecosystems, land use patterns, and energy systems. However, the coastal context is only one way to characterize the many research opportunities in and around Puget Sound; a similarly rich set of important research questions exists for regional atmospheric, terrestrial, and human systems, as well as the interactions across these domains. Indeed, many of the topics identified in this report can also be found among the research gaps and opportunities identified in a recent multi-agency workshop report on hydro-terrestrial modeling (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling 2020), recent DOE workshops on Mountainous Hydroclimate and Urban Scale Processes, and the MultiSector Dynamics 2030 Vision (Reed et al. 2022), as well as other research scoping efforts.

As part of the scoping study, a multi-day workshop was held in March 2022 to engage the community in developing a deeper appreciation of the current state of knowledge regarding human and Earth system dynamics in the Puget Sound region; identifying gaps in scientific understanding, modeling capabilities, measurements, and data; and defining key research needs and opportunities in observing, modeling, and analyzing regional climate, extreme events, and multisectoral dynamics. The scoping study also includes attention given to comparing and contrasting Puget Sound features and research needs with other regions to help identify transferable and generalizable research questions. The ultimate goal of the study is to highlight some of the most promising research opportunities for enhancing scientific understanding of key processes and interactions in the Puget Sound area, with an emphasis on topics that are aligned with DOE's programmatic and mission interests.

## 1.2 Report Contents and Organization

The ensuing sections of this report begin by describing the scoping study approach (Section 2.0). Next, regional systems of interest are described, including the associated scientific understanding and knowledge gaps related to atmosphere and climate, the land surface, coastal and marine processes, and human systems, as well as how these systems are changing over time (Section 3.0). Section 4.0 highlights some of the most notable extreme events in the region, including heat waves, AR, droughts, and wildfires. Finally, Section 5.0 presents key research opportunities for Earth and environmental modeling. Appendix A and Appendix B respectively contain the related workshop flyer and agenda.

# 2.0 Scoping Study Approach

A multi-pronged, integrated approach was adopted for the scoping effort. As shown in Figure 3, this approach consisted of a pre-scoping phase, which included a preliminary literature review and formation of a scientific steering committee; a community engagement phase, which included a multi-day workshop with interdisciplinary experts; a synthesis phase, which combined the literature review, findings from the workshop, and input from the steering committee and other experts to provide an overview of the state of the science, knowledge gaps, and key research opportunities; and an outreach phase, which will include dissemination of this report and its findings via various mechanisms and venues.

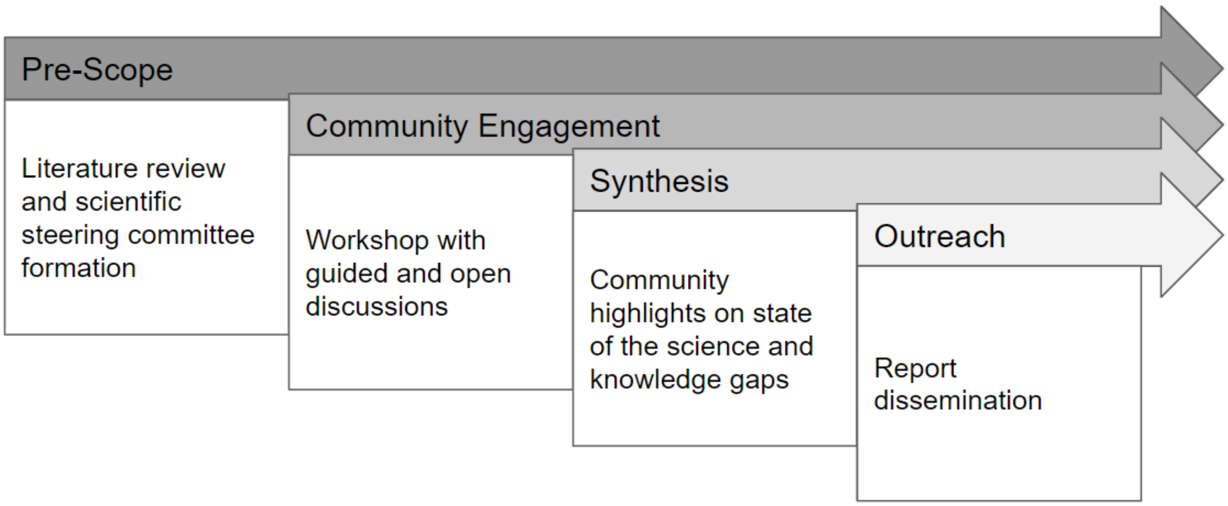


Figure 3. Approach to conducting the scoping study.

A review of relevant peer-reviewed scientific literature was conducted in preparation for the workshop. The process, search terms, and themes are shown in Figure 4. This review was intended to provide a reference bank and general overview of ideas and resources to draw from when organizing the workshop as well as support the review of the current state of the science and knowledge gaps in this report. A general search using thematic search features in the Scopus database was used to identify any themes that may be missing, as well as papers that may not fit a specific theme. A thematic search was conducted to focus on particular topics, using a keyword theme list. Additional papers were added from the Connected Papers tool, identified by the science committee, or referred to during the workshop. Following the workshop, additional papers were collected to assess claims made during workshop sessions to aid in the validity of this workshop report and to supplement the general content about topics discussed. In total, 221 papers were collected and saved in an EndNote library as part of the pre-scope review, and a total of 394 references from the pre-scope review and the full scoping study were compiled into a reference list[1].

[1] A complete reference list from the scoping study can be found at https://docs.google.com/document/d/1sljE4i_5O4oGdJ47EA5bHaWGunSw1qz82h-iYBLjaLE/edit#

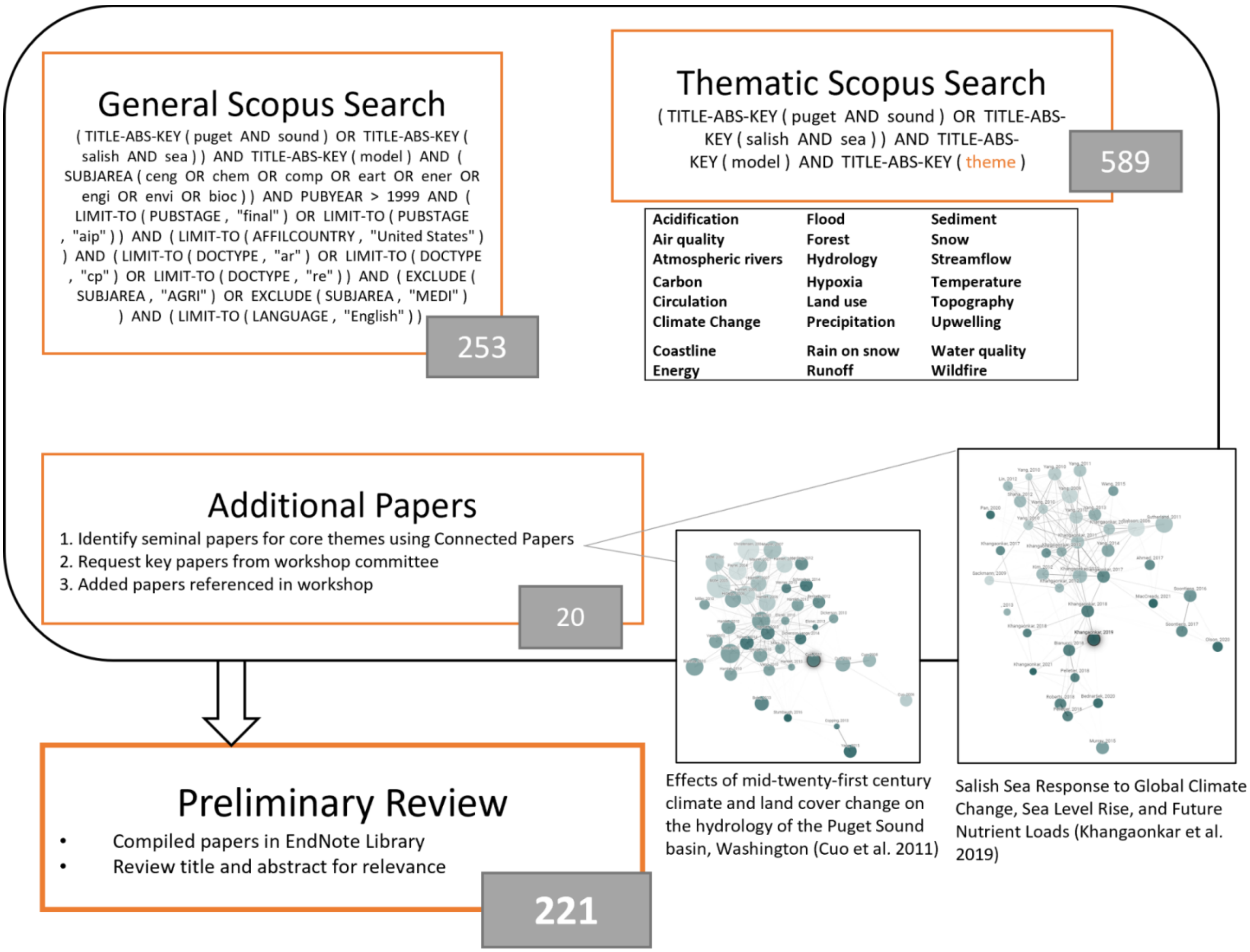


Figure 4. Pre-scope literature review methods and outcomes. See text for details.

Based on the results of the literature review and their personal knowledge and experience, the scientific steering committee worked with the project leadership team and DOE program managers to design a multi-day workshop that would focus on identifying key knowledge gaps and research opportunities in the Puget Sound region (see Appendix A). The workshop was held over three consecutive Mondays in March 2022 using the Zoom.gov platform. A total of 62 individuals participated over the three days. Workshop participants included experts from many different academic disciplines and with diverse professional experience representing universities, federal and state agencies, and key nongovernmental and private sector groups, including individuals who work with stakeholders and bring experience in co-production of knowledge and data to advance and expedite science-to-solutions and research-to-operations-to-research endeavors.

The workshop was organized based on topics identified by the scientific steering committee because they were compelling research gaps that could serve as an effective focus for discussion (see Appendix B). On the first day, the focus was on extreme events in the Puget Sound region, including heat wave and cold-air outbreaks, extreme precipitation and floods, and droughts and wildfires, as well as the interactions of these stressors with human and natural systems in the region. Plenary speakers provided context and some starting points for both plenary and breakout group discussions. A structured Google Jamboard was used to guide discussion and collect information in breakout groups. On the second day, the focus was on some of the key drivers of changes in the integrated human-Earth system in and around Puget Sound, specifically hydroclimatic drivers, atmospheric drivers, and evolving human systems. Plenary speakers again provided context from both the climate and human systems perspectives, and a structured Jamboard was used to guide and capture breakout group discussions. The third day consisted of moderated open discussion to distill knowledge gaps and a group-edited google document was used to identify and capture cross-cutting challenges and opportunities. Throughout these discussions, there was an emphasis on identifying knowledge gaps that aligned with the objectives and interests of DOE's EESM.

After the workshop, the author team and scientific steering committee continued to interact regularly to refine and distill the discussions at the workshop. We developed written summaries of the discussions during the various breakout sessions, contacted a handful of additional experts to reflect perspectives that were not well represented at the workshop, and invited the plenary speakers and other workshop participants to provide additional materials and review the draft report. The document reflects this broad range of input, but decisions regarding the final content were ultimately the responsibility of the author team.

# 3.0 Regional Systems of Interest

## 3.1 Atmosphere and Climate

The Puget Sound region features a maritime climate with wet winters, dry summers, and generally mild temperatures. These and other characteristics are well documented in a large number of online resources (e.g., Encyclopedia of Puget Sound) and peer-reviewed publications. The region is strongly influenced by large-scale variability patterns such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (see, e.g., Moore et al. 2008 or Mote 2003). These patterns have a pronounced influence on seasonal and annual precipitation as well as on extreme hydrologic events such as flooding in the many rivers that drain into Puget Sound (as discussed later in this report). The influence of climate change in the region has also been extensively studied. For example, it is generally accepted that air and water temperatures will warm and that this warming will lead to a higher fraction of winter precipitation falling in the form of rain, leading to cascading changes in land surface hydrology, water resources, and a host of impacts on human and natural systems (Balling et al. 2011; National Climate Assessment 2014, 2018). However, workshop participants noted that work is still needed to better understand potential changes in a variety of large-scale atmospheric circulation patterns and coupled Earth system processes that could have a significant influence on Puget Sound, its watersheds, and their inhabitants—changes such as shifts in patterns such as the PDO and/or ENSO, shifts in storm tracks, or changes in the coastal ocean that influence atmospheric temperature and moisture.

The complex topographic and geographic gradients around Puget Sound often necessitate the use of high spatiotemporal resolution to understand key processes within and across atmospheric, terrestrial, and coastal systems. Downscaling has thus been a key tool for understanding climate variability and change in the region (Gutmann et al. 2014; Jiang et al. 2018). Nested dynamical or quasi-dynamical models using outputs from global climate models (GCMs) and Earth system models (ESMs) can improve the representation of orographic features and fine-scale atmospheric processes, and hence the details of regional precipitation patterns (see Figure 1 for an example in an adjacent region). Statistical-empirical or hybrid approaches can also be useful for assessing the potential impacts of climate change. However, there is no consensus on the best downscaling methods or products for representing specific climate processes or variables (a topic currently receiving attention from the DOE-funded HyperFACETS project), although there have been a few intercomparison studies on combinations of GCMs and downscaling to understand changes in climate in complex terrains (Wood et al. 2004; Mendoza et al. 2015). Additionally, downscaling methods cannot correct all of the errors or biases in large-scale models, they can introduce their own biases, and they fail to incorporate potential upscaled (i.e., regional-to-global) feedbacks. DOE's Energy Exascale Earth System Model (E3SM) has the ability to seamlessly resolve features at high resolution through regional refinement in a global simulation domain (see, e.g., Tang et al. 2019), and the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM; Caldwell et al. 2021) has an ultra-high-resolution convection-resolving configuration capability. Both of these tools could be valuable for exploring some of these processes and uncertainties, and the complex landscapes around Puget Sound could serve as the perfect testbed for comparing and contrasting different modeling and downscaling approaches, including the use of multiscale modeling hierarchies.

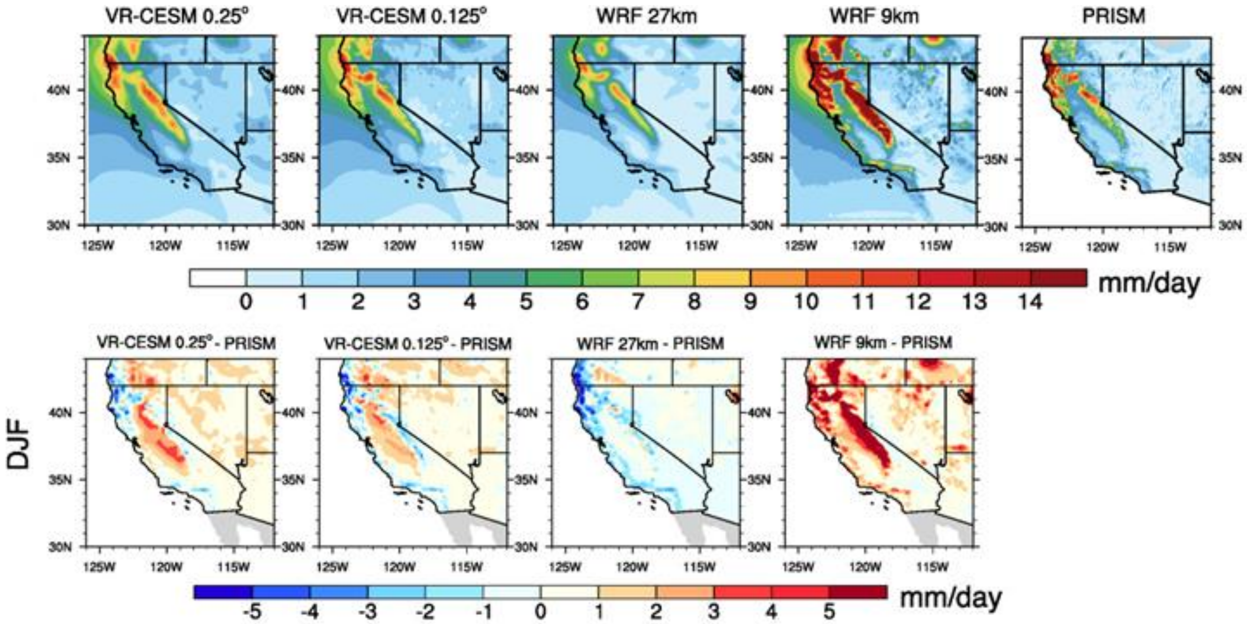


Figure 5. Comparisons of winter (December-January-February) precipitation between regional climate models with variable resolutions and the reference data set from PRISM (Parameter elevation Regression on Independent Slopes Model). Source: Huang et al. 2016.

## 3.2 Hydroclimate, Land Use, and Terrestrial Ecosystems

The large topographic variability and complex land use history of the Puget Sound region have a profound impact on regional hydroclimate and terrestrial ecosystems. As in many other mountainous regions, a considerable fraction of winter precipitation is stored in the form of snowpack in upland watersheds and released during summer months. The range of hydrologic regimes is especially diverse across the 21 watersheds that feed into Puget Sound due to the high topographic gradient—roughly 20 percent of the land area is close to sea level and 20 percent is above 1,200 meters. Many of the larger rivers are managed, although the total reservoir volume is relatively small compared to the amount of water stored in snowpack. Snow-dominated headwater catchments are typically controlled by reservoirs operating for flood control, hydropower, recreation, and conservation; while snow-rain transitional watersheds are generally operated for water supply and contribute to diverse fluvial regimes at the estuaries when finally converging with rain-dominated and mostly urban or agricultural watersheds. It is becoming increasingly challenging to balance these competing needs (Cuo et al. 2011; Polebitski et al. 2011) and to simulate how future flows might change under different scenarios (Cuo et al. 2011; Traynham et al. 2011). The warming climate is anticipated to reduce winter snowpack, further limiting summer flows, as well as raise the temperatures of snow-fed streams and rivers (Lee et al. 2020; Mote et al. 2018; Yan et al. 2021).

Regional land use and land cover in the Puget Sound region have changed dramatically over the past century and a-half to meet the demands of a growing population, and they continue to evolve (Figure 6). Logging has been a dominant industry in much of the Pacific Northwest for many years, leading to significant changes in regional landscapes and ecosystems (Bowling et al. 2000; Gibbons and Salo 1973). Loss of riparian vegetation due to logging, in combination with warmer winter climate and reduced snowpack, has resulted in decreased water availability in summer and exacerbated warming in rivers, particularly in snow-rain transition watersheds

(Yan et al. 2021). Increased riverine thermal input from changing climate and land use will likely affect the heat balance of Puget Sound (Cao et al. 2016), which in turn affects its estuarine ecosystem (e.g., Moore et al. 2015). Economically and ecologically valuable Pacific salmon and steelhead are increasingly stressed, which has led to the listing of many populations under the United States Endangered Species Act and significant investment in restoration efforts (Fullerton et al. 2022). Affected hillslope hydrology compounded with evolving fluvial morphology has also influenced water management and affected the sediment load of rivers across the region (Scott and Collins 2021).

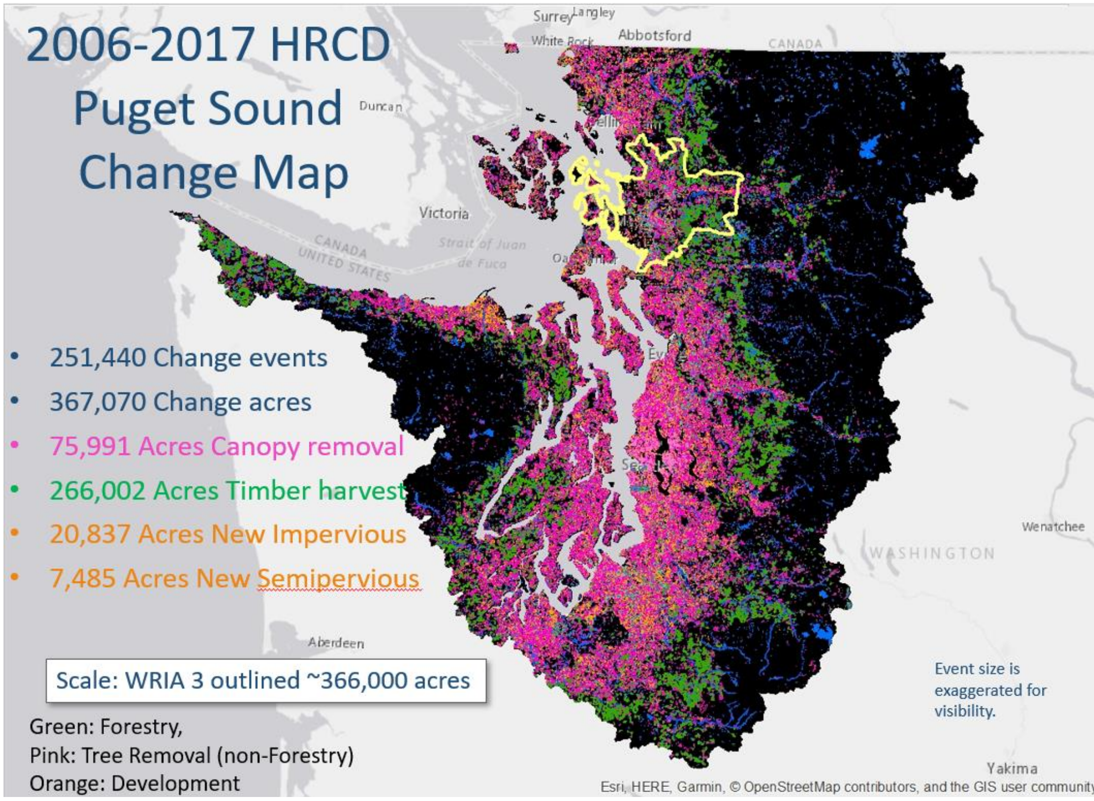


Figure 6. 2006–2017 high-resolution land cover change detection map of the Puget Sound region. Source: Puget Sound National Estuary Program 2020.

Urban development in the Puget Sound lowlands has increased dramatically over the past several decades (Alberti et al. 2004; Hepinstall-Cymerman et al. 2013). This urbanization has had a profound influence on regional hydrology and flood regimes (Cuo et al. 2011, 2009); ecosystem dynamics (Moscrip and Montgomery 2007); river, coastal, and nearshore water quality (Alberti and Bidwell 2005; Feely et al. 2010; Sun et al. 2016); and a host of other environmental processes. Urbanization tends to fragment Earth systems to the point that their environmental functions, such as draining or filtering water, are degraded. Housing density and parcel position have been found to be good predictors of land cover composition changes, with implications for both urban planning and modeling of the impacts of urbanization (Figure 7).

In contrast to climate-related changes, which generally reduce summer water availability, urbanization-related changes are projected to increase annual streamflow in lowland streams and increase the aggregate inflow to Puget Sound (Cao et al. 2016). Simulations focused on urban catchments in the Puget Sound basin (Sun et al. 2016) also suggest that urbanization will have greater effects than climate change on the magnitude and seasonal variability of streamflow, sediment, and phosphorus loads. Brandenberger et al. (2011) reported changes in hypoxia levels in Puget Sound pre- and post-urbanization, while noting the potential influence of climate oscillations when explaining water quality variability. Alberti and Marzluff (2004) concluded that more research on urban patterns was needed to define and predict "human and ecosystem functions in urban ecosystems," and workshop participants indicated that this research gap has only grown over time. Some of the human system dynamics associated with urbanization, such as population dynamics and infrastructure, are discussed in the Human Systems (Section 3.4 below).

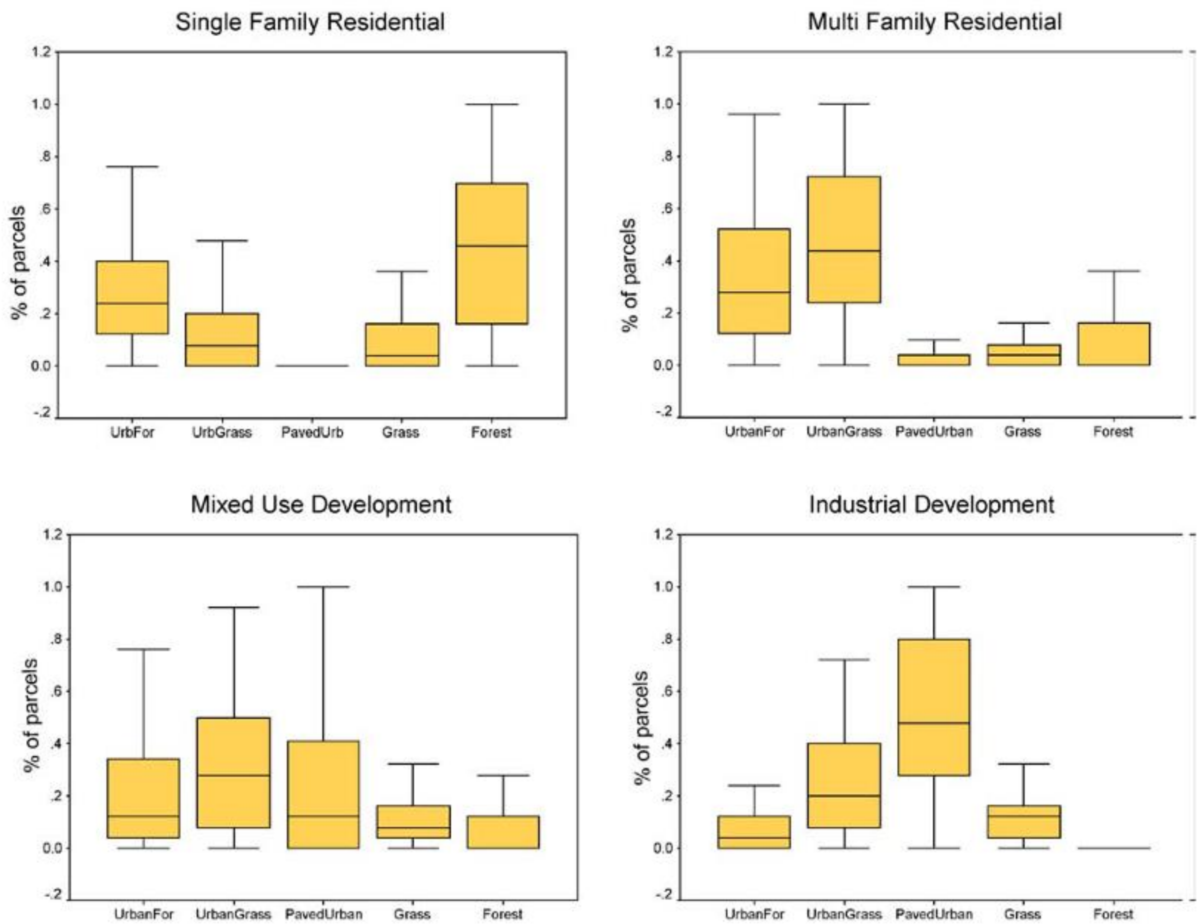


Figure 7. Distribution of land cover across parcels with different land use in King County, WA. Source: Alberti and Marzluff 2004.

The terrestrial ecosystems around Puget Sound have been profoundly impacted by logging, urbanization, water management, and other human activities. A number of groups have developed detailed high-resolution models capable of resolving many of the key land system processes, often with an emphasis on the influence of wildfire, forestry practices, urbanization, and other management decisions on water resources (e.g., the Distributed Hydrology Soil Vegetation Model – DHSVM). As noted above, several tools have also been developed to study land use and land cover changes in the region. In general, however, there has been considerably more attention in the published literature given to Puget Sound coastal and marine ecosystems than to terrestrial ecosystems in the surrounding watersheds. There is an opportunity to leverage, connect, and extend existing tools, including E3SM's land model and other tools that have not previously been used to study Pacific Northwest terrestrial ecosystems in detail.

A number of additional observational, modeling, and knowledge gaps also exist in understanding integrated hydro-terrestrial systems around Puget Sound. For example, despite a number of field campaigns (e.g., OLYMPEX), observations of snowpack, soil moisture, and water quality have major observational deficits that in turn constrain model development, calibration, and validation. Improved modeling approaches for representing hydrological, ecological, and biogeochemical processes in regions with large topographic gradients are also needed, and they need to include the influence of variabilities patterns and the changes induced by long-term warming, human development patterns, and other stressors. There is also a need to improve the coupling of climate projections with water management activities, such as the growth in multisectoral water demands and implications for both water quality and water availability across the region. Projecting future changes in hydropower resources in the context of climate change, land use changes, and competing water management objectives such as flood control is a major challenge for the Pacific Northwest as well as many other regions. Additional research needs identified by workshop participants related to terrestrial systems are described in the final section of this report.

## 3.3 Coastal and Marine

A large number of academic, federal, state, local, tribal, and nongovernmental organizations are also involved in monitoring and modeling Puget Sound itself. For example, multiple groups have developed high-resolution coastal ocean models capable of representing tidal circulations, waves, storm surges, tsunamis, sediment transport, biogeochemistry, and other processes in Puget Sound and the broader Salish Sea (e.g., Salish Sea Model, LiveOcean, SalishSeaCast NEMO Model, PS-CoSMoS). These models require extremely high resolution to account for the complex flow patterns arising from Puget Sound's high tidal range and complex geography and bathymetry. There has also been considerable work done to understand regional sea level rise (e.g., Miller et al. 2018; Seattle Public Utilities map of Sea Level Rise; NOAA Sea Level Rise Viewer), and regional planners have started to incorporate these projections into decision-making about urban planning and adaptation (e.g., Raymond et al. 2018; Feifel and Braddock 2021; Island County Sea Level Strategy 2020). Fewer entities have considered the combined impact of sea level rise, climate change, and land use land cover change on salinity intrusion, though it has been shown that all three processes are important to consider (Yang et al. 2015).

Puget Sound is home to a huge range of species, with complex food webs spanning the nearshore, pelagic, and intervening areas, all of which are strongly influenced by the influx of freshwater, sediments, and nutrients from rivers and nearshore environments (Ruckelshaus and McClure 2007). As in many heavily developed coastal environments, Puget Sound ecosystems have been impacted by a variety of human activities, including forestry, agriculture, urban development, dams, and the attendant changes in runoff, sediment, and pollutants. Key conservation species like the salmon and orca, both of which have been declining in numbers, have been a major driver for understanding regional hydrology and water quality (Figure 8). Puget Sound is a hotspot for early market tidal energy development (Yang et al. 2021), and the physical and ecological implications of widespread tidal energy deployment are largely unknown. A number of groups, such as the Nature Conservancy's Stormwater Heatmap, and entities such as the Puget Sound Partnership and its Puget Sound Ecosystem Monitoring Program, have developed tools to help understand Puget Sound ecosystems and the factors influencing them. The shared water boundary with Canada creates interesting transboundary management challenges across terrestrial, freshwater, estuarine, and coastal ecosystems.

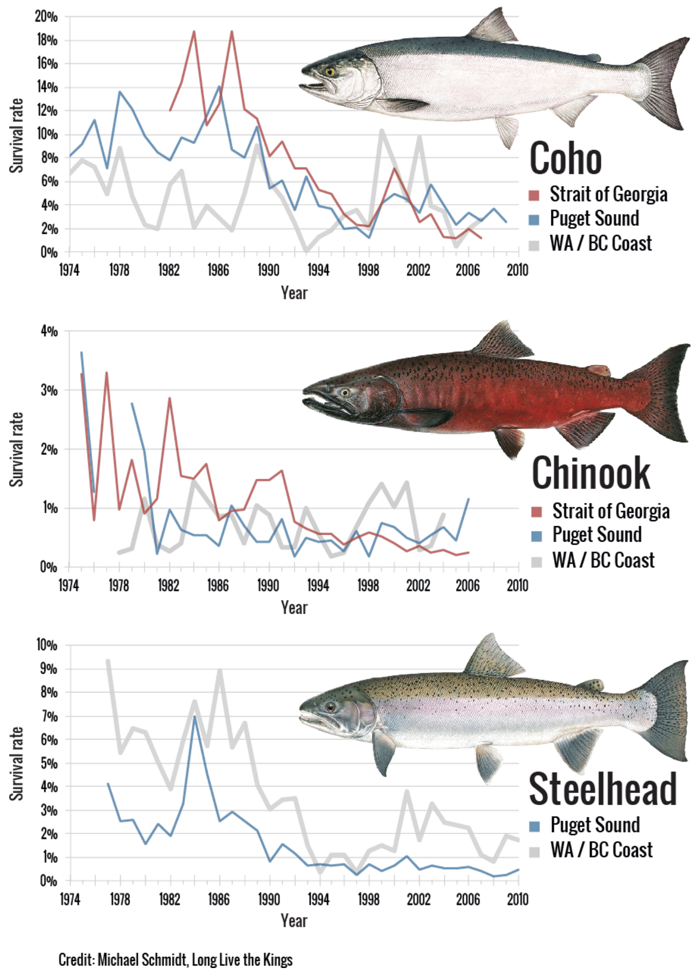


Figure 8. Survival rates of three species of salmonids—the Chinook, the coho, and the steelhead—have experienced sharp declines in Puget Sound since the 1970s. Source: Adapted from Salish Sea Marine Survival Project by Long Live the Kings.

While robust data and modeling capabilities exist for many of the systems in Puget Sound, there are still a number of capability and knowledge gaps, as well as a need to better understand and simulate how hydroclimate, riverine, marine, and human systems interact. For example, there is a need to better model surface and groundwater interactions as well as bi-directional subsurface exchanges along the shoreline, especially with respect to saltwater intrusion and lowland agriculture impacts. Modeling within ecosystems has strengths, but there is need for better coupling across ecosystem boundaries, especially between small-scale ecosystem models and larger representations of climate in the nearshore area and the freshwater-estuary interface (e.g., marshes). Tidal cycles and their interactions with river discharge, wave, extreme weather events (e.g., wind) and sea level rise need to be more comprehensively represented, as well as the potential environmental effects of tidal energy development. Additional study of the potential impacts of sea level rise will also be critical to understand the visibility and severity of impacts in the region, especially with highly urbanized areas occupying a significant portion of the interior coastline.

## 3.4 Human Systems

The previous sections have already highlighted several important human activities and stressors in the Puget Sound region, such as water management, forestry, and urbanization. Indeed, many of the region's environmental systems have been profoundly shaped by human development patterns and other activities. Many human activities are also influenced by climate variability and long-term warming, along with other short- and long-term Earth system processes. The Puget Sound and broader Pacific Northwest region have an extremely active research community focusing on human-Earth system interactions. However, many data, knowledge, modeling gaps remain.

Human habitation in the Puget Sound region dates back over 10,000 years. The original Native American inhabitants have been called Puget Salish, Southern Coast Salish, or Lushootseed people, with tribes including the Nisqually, Skagit, Snoqualmie, and others. The first European settlements appeared in the mid-19th century and expanded rapidly with the Gold Rush. Population has surged again over the past several decades alongside economic growth, especially in urban centers, with additional growth being forecast in the decades ahead (e.g., PSRC Macroeconomic Forecast 2018, VISION 2050). Factors shaping population shifts and the accompanying development patterns include the constrained geography of the region and policies affecting the region's tribes and communities of color (D'Aquila 2022; NWIFC 2014). As climate change leads to increasingly inhospitable conditions in other regions, western Washington State has been viewed as a potential climate refuge (Bryan 2021; Policygenius 2022), but understanding the processes that drive migration at different scales and the potential role of climate in shaping those processes remains an outstanding research challenge (Saperstein 2015).

One unique feature of human systems in the Puget Sound and broader Pacific Northwest region is the dominance of hydropower in the regional energy mix; it represents approximately 66 percent of net electricity generation in the state (EIA 2022; also see Figure 9). Wind and solar resources managed by utilities serving the Puget Sound region are growing rapidly, with installations primarily located in eastern and central Washington (see, e.g., PSE 2022). Because many parts of the Pacific Northwest feature peak energy demand during the winter, hydropower is typically exported to California during summer months, when demands there are highest (2021 Northwest Power Plan; Western Energy Imbalance Market). Along with the impact of climate change on regulated flow and hydropower (Lee et al. 2016), markets can also affect flow regimes (Kern et al. 2012). For instance, recent changes in markets and electricity generation portfolios have been shown to decrease weekly release peaking in rivers managed for hydropower (Déry et al. 2022). Washington State has adopted aggressive targets for decarbonizing regional energy systems, and the large existing fraction of renewable energy production in the region should generally make decarbonization easier than in some other regions (de Chalendar et al. 2019). However, it also means that further carbon emissions reductions will have to come from other sectors, such as transportation, which creates different energy transition challenges than in other regions of the county where fossil fuels underpin electric power production (see, e.g., E3 2019).

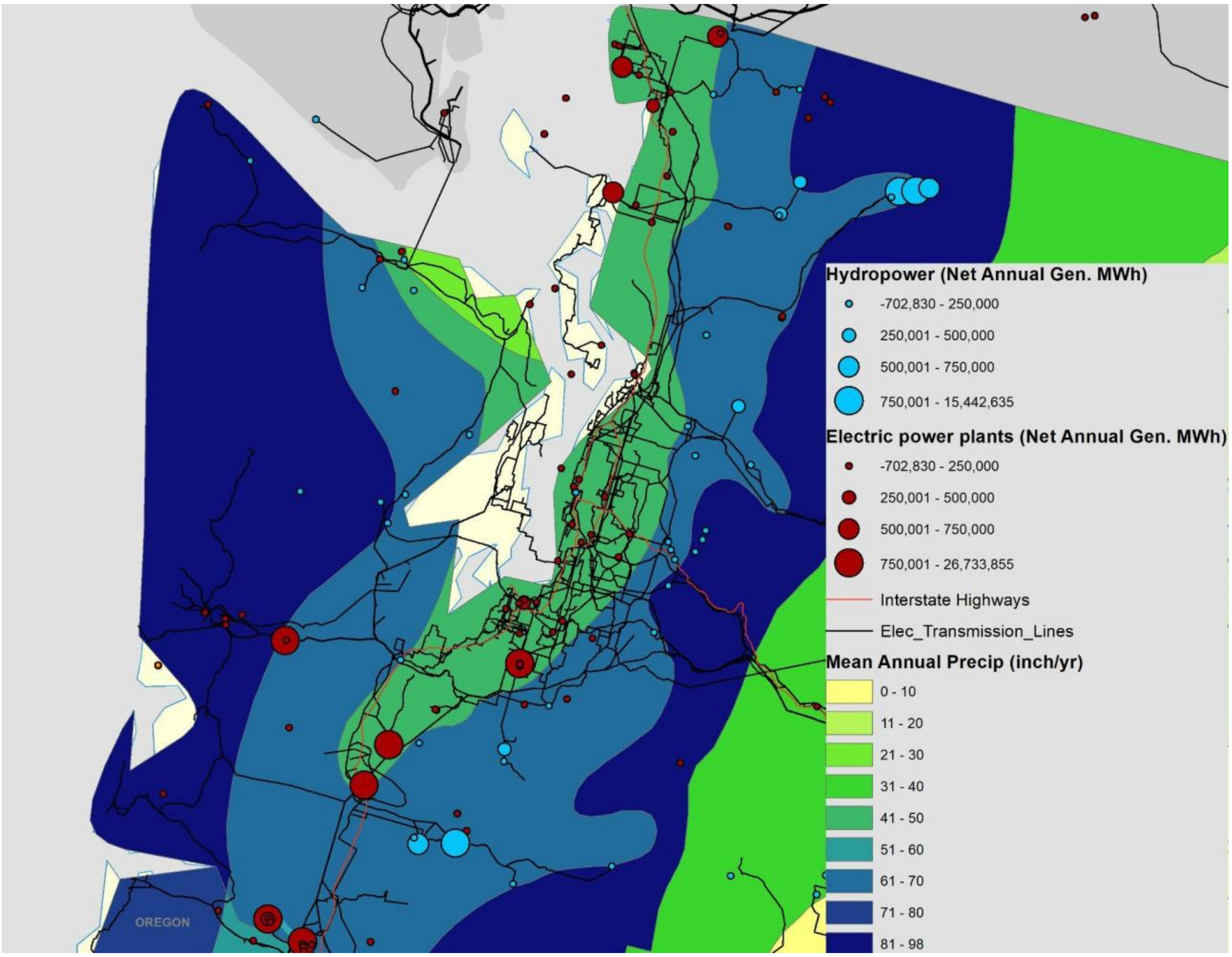


Figure 9. Electricity infrastructure in the Puget Sound and close proximity. The representation of main highways and electricity transmission and distribution lines highlights the dependencies in how human systems are connected. Data sources: S&P Global Platts 2018, NOAA/NCEI Climate Division.

Considerable attention has been given to understanding how climate change will affect human systems across the Pacific Northwest (e.g., Mauger et al. 2015). For example, air temperature increases are expected to decrease winter electricity demands but increase summer demands (2021 Northwest Power Plan). Precipitation, runoff, and flood frequency changes are informing the design of stormwater (e.g., Rosenberg et al. 2010) and port infrastructure (Simpson 2012; Figure 10) and leading to recommendations to increase culvert width to maintain fish passages and reduce damage to road infrastructure in rural to suburban areas (Climate Robust Culvert Design Project; Mauger et al. 2021; Wilhere et al. 2008). The differential climate risks faced by communities across Washington State have also been examined and there are ongoing efforts to understand differential impacts on human well-being (e.g., Climate Impacts Group et al. 2018; GODEEP). However, impact studies typically look at impacts on a single system or sector across a small set of scenarios, typically with fixed assumptions about how other processes and interactions might change or how systems might evolve or adapt. Impact studies also tend to be end-user oriented, with limited influence on improving fundamental understanding of human and coupled human-Earth system processes. A more comprehensive description of human-Earth system interactions across Puget Sound would include accounting for the complex interactions within and among physical infrastructure, demographic and economic changes, land use change, technology development and deployment, resource use, and policy and management decisions of all sorts. These are many of the same topics, sectors, and challenges that the MultiSector Dynamics Community of Practice has been discussing more broadly as it seeks to develop frameworks for modeling and understanding the co-evolution of human and natural systems across different scales and geographic contexts (Earth's Future 2022). Workshop participants noted that certain features of the Puget Sound region, such as the high fraction of hydropower in its energy mix (and hence strong energy-water linkages) and the relatively sharp urban-to-rural gradients in regional development patterns, could make it a particularly interesting testbed for exploring multisector interactions.

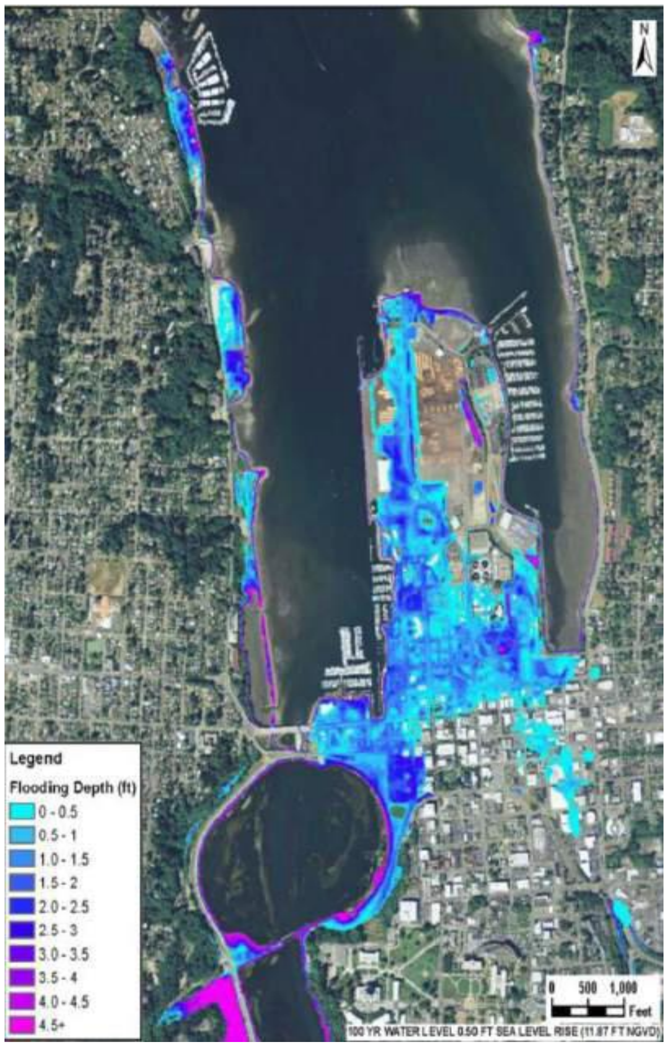


Figure 10. Projected area and depth of flooding in the City of Olympia, Washington, during a 100-year flood event with +6 inches of sea level rise. Source: Simpson 2012, reproduced from Mauger et al. 2015.

Another overarching theme noted during the workshop was the importance of including human activities more explicitly in coupled Earth system modeling, both to improve the ability of models to inform decision-making and to account for the dynamic feedbacks between human decisions and environmental trends. DOE's E3SM already includes several human system processes, including water management (MOSART-WM) and agricultural decision-making (Kyle et al. 2011), at spatial and temporal scales appropriate for global Earth system modeling. Other DOE projects, such as Integrated Multisector Modeling and Program on Coupled Human and Earth Systems, have developed approaches for coupling human and natural system models to exchange information at the much higher resolutions that many human systems require. However, as spatial domains shrink and spatial resolution grows, there remain unresolved questions around the most appropriate way to represent upscaled feedbacks or interactions with other regions. In the context of Puget Sound, this could include things like understanding migration patterns or the impact of supply chain disruptions on regional economic activity. Another idea proposed at the workshop is to mine available data and regional studies that relate the response of human systems to climate stress. Artificial intelligence (AI) and machine learning (ML) are emerging methods to explore potential interactions by representing human actors in human-Earth system models (e.g., Ekblad and Herman 2021).

Workshop participants also noted that stronger engagement of the social sciences would be an important prerequisite for improving how human systems and their interactions with the environment are represented in models. For example, understanding the factors driving urban development patterns or the rate of adoption of new technologies requires understanding and accounting for human decision-making at many levels. Biedenweg (2017) looked at the influence of demographics on environmentally oriented human well-being metrics across the Puget Sound region but found no robust relationships and noted high variability in the results. A few efforts in other regions have started representing human decision-making in models, such as the influence of changing flood risk patterns on real estate markets (Chandra-Putra & Andrews 2020). Representing decision-making in models more holistically is a particularly important and challenging topic, especially in the context of climate change mitigation and adaptation (see, e.g., Moss et al. 2013). However, we currently lack adequate understanding of the many factors influencing decision-making, such as scales of governance, institutional arrangements, formal and informal norms, culture, perceptions, values, etc.

A final challenge associated with modeling human activities, decision-making, and interactions with Earth systems is the presence of many deep uncertainties (see, e.g., Marchau et al. 2019). Characterizing uncertainty can become increasingly difficult as the number of systems being simulated increases. The community has been developing and testing frameworks and approaches for doing so in a multisector context, and some best practices are beginning to emerge (e.g., Addressing Uncertainty in MultiSector Dynamics eBook). An overarching need in progressing forward with improving combined human system and natural system models is to bring together researchers with human system-oriented science questions and researchers with Earth system science questions to develop modeling experiments that can begin to construct linkages and quantify uncertainties relate to different use cases.

# 4.0 Extreme Events and Impacts

As in many regions, some of the most consequential interactions between human and natural systems across Puget Sound occur in the context of extreme weather or climate events that lead to major damage or disruptions. Projecting future changes in these events is difficult but critical for understanding the potential risks to human life, well-being, and livelihoods, as well as critical infrastructure, and to aid in planning for mitigation or adaptation measures across multiple time scales (Santella et al. 2009; Hallegatte et al. 2007; Hanna and Marqusee 2022; Copping et al. 2018). Extreme weather and climate events have of course happened throughout time, and some are even critical for long-term ecosystem health. However, many types of events are becoming more frequent and more intense due to human-induced climate change (Trenberth et al. 2015), and explicit attribution of extreme events to human activities is a maturing field (Swain et al. 2020; Van Oldenborgh et al. 2022).

The extreme events that received the most interest and attention before and during the workshop were related to regional hydroclimate, including atmospheric rivers (ARs), rain-on-snow (ROS) events, and the attendant flooding and flood risks. This focus on hydroclimatic extremes is not surprising given the cascading impacts that hydrologic changes can have across the Puget Sound region’s interconnected systems. Other extreme events identified in the literature review and discussed at the workshop include heat waves, cold snaps, droughts, and wildfires, all of which are associated with significant impacts on regional inhabitants, infrastructure, and ecosystems. In many cases, long-term stresses associated with human activities are increasing the attendant vulnerabilities and risks, such as through the proliferation of buildings at the wildland-urban interface. The sections below summarize the mechanisms, implications, and uncertainties associated with the extreme events discussed at the workshop, including how human activities might be intentionally or unintentionally exacerbating or mitigating the associated risks. Additional information is available in the cited references as well as the extended bibliography and the end of this report.

## 4.1 Heat Waves and Cold Snaps

The Puget Sound region typically experiences some of the mildest summer temperatures in the country. As a consequence, there are fewer adaptation options for extreme heat (such as air conditioning) than in other regions, and the potential impacts of extreme heat on regional systems can be more severe (Arnold et al. 2022; Young 2012). Although heat waves in western Washington State have been rare historically, they have been increasing in recent years, with a sharp uptick in the number of days per year with maximum temperatures exceeding 90 degrees Fahrenheit (First Street Foundation 2022a; RiskFactor). Night-time heat events have occurred even more frequently than daytime heat events in the last few decades (Bumbaco et al. 2013), which is consistent with the rate of increase in summer minimum temperatures being about three times greater than in summer maximum temperatures over the historical record.

Public interest and research activity increased sharply after a record-setting heat wave that occurred in 2009 (e.g., Bumbaco et al. 2013), a heat wave in 2015 that was accompanied by severe drought (Steel et al. 2019) and a protracted marine heat wave (Bond 2021), and most recently after a truly exceptional heat dome event in late June 2021 that shattered temperature records across the state with temperatures 15–20°C above normal maximum temperatures (Figure 11). The 2021 event led to far-reaching impacts across many human and natural systems, including water resources, agriculture, energy production, human health, and terrestrial, aquatic, and marine ecosystems (Raymond et al. 2022; Suryan et al. 2021; White et al. 2022; Washington State Department of Health 2021). An attribution analysis determined that there was little to no chance of an extreme heat event of this magnitude occurring without human-caused climate change as a driver (Philip et al. 2021), thereby highlighting the role of human activities in driving long-term changes in extreme heat.

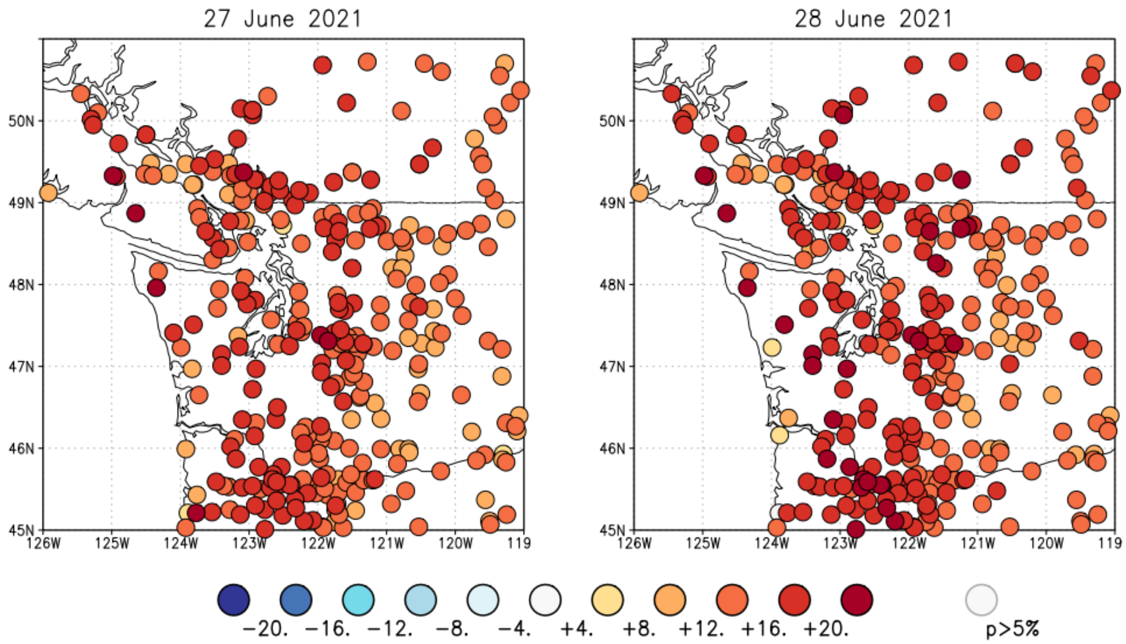


Figure 11. Observed daily maximum temperature anomalies in degrees Celsius for June 27 and June 28, 2021, relative to the normal maximum temperature for the same time of year. Source: Philip et al. 2021.

The mechanisms and drivers of heat waves in the Pacific Northwest are fairly well understood: the most extreme summer temperatures occur when ridging dominates the atmospheric flow, and the highest daytime temperatures in the Puget Sound lowlands are associated with easterly or northeasterly winds that drive downslope and offshore flow. However, the characteristic regional atmospheric circulation pattern associated with “hot day” events differs from that associated with “hot night” events, and there can be additional amplifying or mitigating factors such as soil moisture content. Despite this general understanding of the mechanisms and interactions with other systems, several modeling challenges remain. In the current generation of climate models, representing synoptic-scale ridging and blocking events remains a key challenge (see, e.g., Liu et al. 2022). A multiscale modeling of heat waves is a more general research need (Grotjahn et al. 2016). Additionally, given the substantial natural variability associated with atmospheric circulation patterns, large ensemble simulations are typically needed to isolate the response of features such as ridging and blocking to anthropogenic forcing. As a result, considerable uncertainties exist in the projections of future heat waves in many regions, including the Pacific Northwest.

An additional and equally important modeling challenge is understanding the potential interactions with and impact of heat waves on other systems in the Puget Sound region. Heat waves interact with other Earth systems including the marine environment, wildfires, drought (Mazdiyasni and AghaKouchak 2015), and other vegetation impacts and feedbacks (Klein et al. 2022). Heat waves also have societal implications, which have generally not been studied in depth, including public health, productivity and economic impacts, energy systems impacts and adaptations (such as installation of air conditioning), and public perceptions of climate change. It is generally well understood that urbanization leads to higher temperatures where population densities are also highest, exacerbating the impacts of extreme heat (Qian et al. 2022). The role of urbanization on heat waves around Puget Sound has been explored in the context of urban planning practices that can alleviate the human stresses—practices such as green parks (e.g., Stone et al. 2010, King County Heat Mapping project), but remains an area to be further examined. It has also been suggested that increases in the frequency of extreme heat in the Puget Sound region may reduce its attractiveness to climate refugees (Milman 2021).

Cold snaps were not discussed in their own breakout session at the workshop, but were touched on in the same group that discussed heat waves. Extreme cold is generally expected to lessen in severity in the Puget Sound region over time, with extreme cold conditions projected to become more rare (Mauger et al. 2015; Snover et al. 2005). This change over time will have interactions with other human systems, including winter-time electricity consumption, public health, and infrastructure design. The mechanisms and drivers of cold snaps are fairly well understood, cold air flowing through mountain gaps being one of the key processes (see, e.g., Sheridan and Lee 2018). However, climate models typically over-predict the intensity of cold snaps compared to observations, and these cold biases persist even with downscaling (Leung and Qian 2003), in part because there tends to be insufficient blocking of cold air by terrain to the north and east of Puget Sound and hence an unrealistically high frequency and intensity of cold-air incursions. These results suggest that significant uncertainties remain in accurately simulating both the large-scale flow patterns and detailed interactions with topography that drive extreme cold snaps, as well as extreme heat waves.

Workshop participants also noted that the topography and physical geography of the Puget Sound region, with two mountain ranges surrounding lowlands and a fairly narrow strip of water, has important effects on the development and spatial characteristics of temperature extremes. Gaps in topography, such as the Fraser River Valley, link areas with very different air masses, and the flows through these gaps can affect the development and persistence of extreme events (Environment Canada and U.S. Environmental Protection Agency 2014). The relatively cool and constant temperature of the water in Puget Sound, as well as the presence of steep topographic temperature gradients, also creates refuges for people and animals capable of moving to escape extreme temperatures. As noted above, built-up areas can also have a significant influence on local temperatures. Given all of these challenges and uncertainties, workshop participants noted that Puget Sound could serve as a powerful testbed for improving the ability of climate models to represent the multiscale processes that drive extreme temperature events.

## 4.2 Extreme Precipitation and Runoff

ARs, ROS events, and the associated riverine flooding were the subject of some of the most active discussions before, during, and after the workshop, both in terms of their impacts and outstanding research needs. While these processes are not unique to the Puget Sound region, they do occur frequently and can have outsized impacts due to the region’s geography. Hence, it could be a natural laboratory for observing and modeling key processes shaping these events across multiple scales.

ARs are filamentary corridors of moisture transport that are responsible for a majority of the extreme precipitation events along the U.S. West Coast (see Figure 12), as well as several other regions around the world. The relatively lower-elevation Cascade Range is particularly conducive to intense AR precipitation (Rutz et al. 2014; Chen et al. 2018). The mechanisms behind ARs, the atmospheric circulation patterns that create them, and their connection to sea-surface temperatures (SSTs) are generally well understood (Ryoo et al. 2015; Chen and Leung 2020; Tan et al. 2020). However, large gaps exist in our understanding of their behavior and their impacts, especially as they make landfall in regions that feature complex topography. Studies have shown that enhanced model resolution reduces errors in simulating historical ARs, particularly because of the improved ability to simulate orographic processes (Huang et al. 2020). Additional knowledge gaps include those related to understanding AR moisture uptake along its path, especially over oceans (L'Ecuyer et al. 2015), and improved validation data and techniques (Cannon et al. 2017), including approaches for identifying ARs from meteorological fields (Shields et al. 2018). The winds associated with ARs can also cause damage and could potentially increase AR-induced coastal flood risks, but only a few studies have examined AR winds (e.g., Waliser and Guan 2017). Extreme precipitation and river discharge anomalies, like those observed during the 2014–2016 marine heat wave, can have major effects on circulation, ecosystem productivity, and biogeochemistry in the downstream Salish Sea estuarine ecosystems (Khangaonkar et al. 2021).

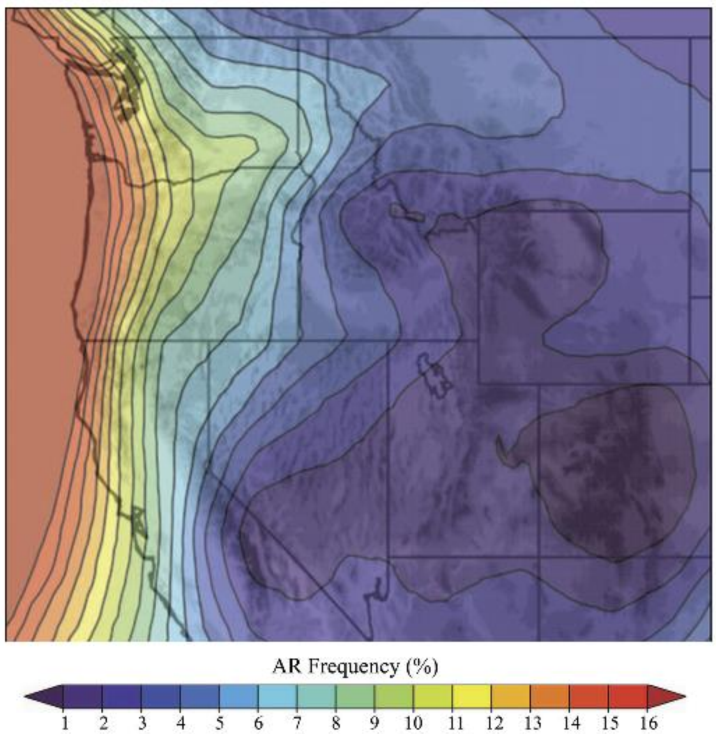


Figure 12. AR frequency based on IVT250, which is strongly correlated with cool-season precipitation and defines an AR as a contiguous region ≥2,000 km in length with integrated vapor transport (IVT) ≥ 250 kg m−1 s−1. Source: Adapted from Rutz et al. 2014.

An additional, and consequential, uncertainty is how AR events might be changing. Sensitivity studies have been performed with increased SSTs (Chen and Leung 2020) and coupled model simulations under various climate change scenarios (Espinoza et al. 2018; Gao et al. 2015; Hagos et al. 2016). These studies suggest that climate warming is increasing the number of ARs as well as their moisture transport and precipitation totals, but they also indicate that dynamical changes may modulate the latitudes of their landfall. Some studies project stronger winter ARs over the West Coast mountains by the end of the 21st century (Gershunov et al. 2017; Rhoades et al. 2020).

The influence of AR intensity, frequency, and landfall duration on snowpack is another key question, especially given the importance of snowpack for regional water resources. Satellite observations can accurately determine the freezing level (Cannon et al. 2017), but there are limits to current data availability and modeling capability. Long-term observations suggest that AR days are responsible for 34 percent of seasonal snowfall in the Cascade mountain range (Hu and Nolin 2019). A strong relationship is also found between ARs and winter snowpack in dynamical modeling, although no clear trend was found between ARs and snowpack during the spring season, likely due to variations in freezing level and the form of precipitation (Goldenson et al. 2018). In parallel to ARs' association with flood hazards, ARs play a key role in drought alleviation in the Pacific Northwest, where 60 percent –74 percent of all persistent drought was terminated by the arrival of AR storms (Dettinger 2013).

ARs are also responsible for many ROS events that frequently occur along the mountain ranges of the Pacific coast and have received considerable attention due to their potential to drive major flooding episodes (Li et al. 2019; Sun et al. 2022). The Oroville Dam failure in February 2017 with a repair estimate of $1.5 billion and evacuations of about 190,000 people is a notable example of ROS floods that have major socioeconomic impacts. An examination of ROS events at more than 4,000 sites in the western United States from 1949 to 2003 found a decreasing trend in ROS events at lower elevations, associated with decreased snowfall and a shorter duration of snow cover on the ground under warmer climate conditions (McCabe et al. 2007). Simulations of ROS events in the future warmer climate also suggested less frequent ROS in the Pacific region due to its warmer winter conditions (Musselman et al. 2018).

Considerable uncertainties remain, however, in predicting individual ROS events and projecting how they might change in the future. As with ARs, the combination of large elevation gradients, a maritime climate, complex regional land use and land cover patterns, and local expertise makes the Puget Sound region a particularly attractive location to advance understanding of the complex processes that drive ROS conditions. For example, the relatively mild winter temperatures create challenges in simulating snowpack dynamics, because the energy balance dynamics of snowpack is sensitive to even small errors in atmospheric forcing when temperatures are at or near 0°C (Raleigh et al. 2016; Sun et al. 2019). In regions that have complex topography it is also more challenging to resolve warm rain processes that involve many interacting microphysical processes (Zhang et al. 2019), leading to greater uncertainties in the amount of rainfall during ROS events. There are also uncertainties in the conditions (rain volume and temperature, antecedent snowpack, site elevation, etc.) under which runoff is more likely to be enhanced by accelerated snowmelt versus diminished by snowpack by absorbing or freezing a portion of the rain. Forest alterations from natural and human disturbances (e.g., fire, clearcut logging) can modulate ROS events by influencing snow accumulation and melt, and ROS runoff can in turn directly affect soil moisture, which plays a key role in vegetation-precipitation and vegetation-climate feedbacks (Sun et al. 2022; Varhola et al. 2010). Finally, observational data sets on climate, snowpack, and runoff under ROS conditions are very limited, especially in the snow-rain transition zone (e.g., 300–1500 m) where ROS is most common and most sensitive to changes in climate.

## 4.3 Flooding

While ARs and ROS events are scientifically interesting, much of the interest in better understanding these phenomena stems from their key role in driving major flooding events. A continental United States-wide analysis (Sun et al. 2022) suggested that the 100-year 24-hour extreme runoff events are typically highest in magnitude along the mountains of the west coast as a result of ROS events (Figure 13). However, connecting ARs and ROS events to flooding and other impacts is a main challenge at the scale of existing global Earth system models. Complex terrain across landscapes of the Puget Sound basin leads to strong heterogeneity in the spatiotemporal distribution of atmospheric forcing (precipitation, temperature, and radiation fluxes), vegetation cover, soil moisture, snowpack dynamics, runoff generation, and other processes that contribute to riverine flood dynamics (Cao et al. 2016, 2020; Yan et al. 2021). For example, variations in snowpack can occur at a small hillslope scale (10–100 m) in mountainous regions, resulting in significant observed variability in snow depth (Clark et al. 2011; Currier and Lundquist 2018). Understanding and finding ways to represent these processes in models, including where ultra-high resolution is needed and which subgrid parameterizations are most appropriate, will be crucial for improving projections of future flood risk in the Puget Sound basin.

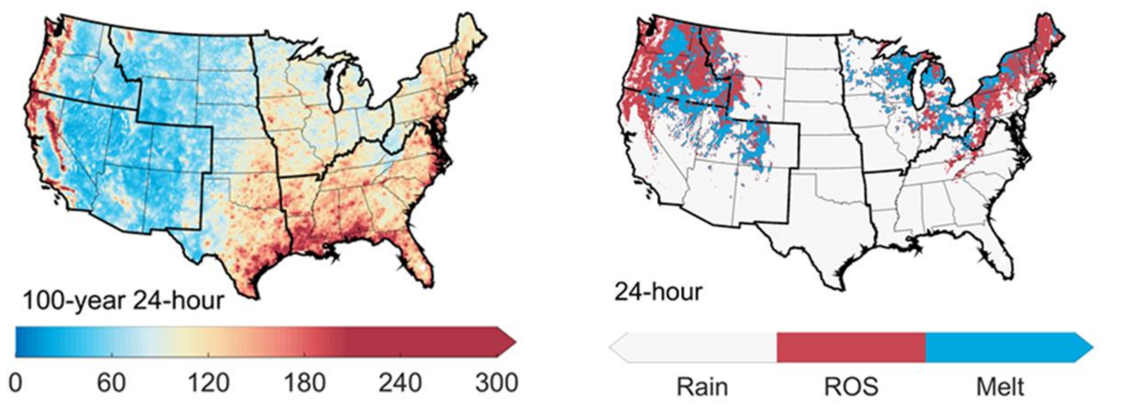


Figure 13. 100-year 24-hour extreme runoff events (in millimeters) and the dominant mechanism over the continental United States. Source: Sun et al. 2022.

In addition to high river discharge (i.e., fluvial flooding), landscapes throughout the Puget Sound watershed are exposed to flooding driven by extreme precipitation (pluvial flooding), and/or king tides and storm surges (coastal flooding). Many low-lying coastal areas are already affected by the co-occurrence of these phenomena, foreshadowing future scenarios of intensified compound flooding along the coast under sea level rise (Hamman 2012; Mauger et al. 2015), which is projected to be as large as 24 inches in the Pacific Northwest during the 21st century (Mauger et al. 2016; Sweet et al. 2022). The complex coastal environment of Puget Sound, with its large tideflats and varying degrees of subsidence or uplifting (Newton et al. 2021), adds intricacy and challenges to predicting flood events near the shoreline. Coastal models operating at the regional or basin-wide scale do not typically have adequate nearshore resolution to simulate the details of coastal flooding, but unstructured grid frameworks can be applied to yield accurate simulations at the scale of the entire Puget Sound (Yang et al. 2019, 2020) and to resolve interactions with coastal river floodplains and project the potential influence of sea level rise on the scale of an individual river delta (Yang et al. 2012; Yang et al. 2015). Extracting key elements from these fine-scale models to entire deltas, regions, and ultimately global scale models is a major challenge for predicting the mechanisms and impacts of coastal and inland flooding. Subsurface dynamics (e.g., seawater intrusion, surface and groundwater interaction) are also important processes to capture, but to date this has only been done at a smaller scale of a small floodplain plot (Yabusaki et al. 2020).

The challenges associated with simulating urban flooding are in many ways greater still, given the need for extremely highly resolved climate data, high-resolution land use and land cover data to characterize human development patterns, and high-resolution modeling tools capable of simulating relevant features and processes—which for many urban areas around Puget Sound can include coastal and riverine flooding in addition to pluvial flooding driven by highly localized extreme precipitation. Flash floods from intense rain events can be exacerbated by reduced soil water storage from impervious surfaces and shortened overland runoff paths in urban drainage systems, and these details can vary considerably depending on infrastructure age, stormwater system design, and many other detailed factors. The timing of overland flooding can also be quite different from that due to coastal storm surge, king tides, and flooding from rivers swollen by upland precipitation. Finally, urban flooding can be associated with large pulses of nutrients and pollution from surface contaminants, sewage, and other sources, all of which end up in Puget Sound.

While there has been considerable progress in simulating riverine and coastal flooding, capabilities for predicting or projecting future changes in urban and compound flooding events are much more limited. More difficult still is simulating the potential influence of climate change, sea level rise, urbanization, and other long-term trends on compound flooding. Coupling of land, river, atmospheric, and coastal hydrodynamic models has only been explored in a one-way manner in Puget Sound (Yang et al. 2015). Capabilities in modeling the hydrodynamics and interactions of these processes at the tidal transition zone are lacking for accurately predicting total water levels, inundations, waves, and saltwater intrusion in the highly developed Puget Sound lowlands, as are assessment tools to understand feedbacks and evaluate the mitigation strategies (e.g., forestry management for wildfire, riparian and river restoration, etc.). Improved understanding of the influence of extreme precipitation and flooding on river biogeochemistry and the chemistry of the water entering Puget Sound is a closely related research challenge.

Human safety, utilities, and access to critical services all rely on accurate flood predictions, warnings, and long-term infrastructure adaptations for resilience. Many rivers throughout the Puget Sound watershed have dams for hydropower or flood control, but some of these systems are aging and operating rules may need to be updated to account for changes in flood risks. In addition to climate warming and the attendant hydroclimate changes, historical channelization of rivers and widespread land cover and vegetation changes alter water flow patterns and can increase water velocity, despite intentions to prevent flooding. Many restoration projects and partnerships are under way to restore degraded systems using both advanced engineering techniques and nature-based approaches (e.g., Puget Sound Restoration Fund), as well as the integration of social science (Biedenweg et al. 2021). Development patterns also continue to evolve, and flood risks are increasingly being taken into account when making land use and infrastructure decisions (e.g., Floodplains by Design; King County Sea Level Rise Risk Area; Binder and Morse 2016). Very few of these human systems and processes are explicitly included in models, and there are significant research (and research-to-operations-to-research) opportunities in modeling the impacts on and responses of human systems to flooding and other extreme events.

Two additional topics that were discussed briefly by workshop participants in the context of flooding were landslides and sediment transport. The physiography and geology of the Puget Sound region features a lot of steep slopes and exposed glacial deposits prone to erosion, and intense precipitation and flooding can exacerbate the attendant landslide risks (Moon et al. 2011; Scott and Collins 2021). Following three weeks of heavy precipitation in 2014, a large mudslide near Oso, Washington, killed more than 40 people and caused significant property damage. While soil saturation was determined to be the primary factor in that event, other factors were at play, including altered groundwater migration, weakened soil consistency because of previous landslides, and changes in hillside stresses (Stark et al. 2017). Making direct connections between landslide risks and extreme precipitation events, or other human and Earth system processes, is challenging because hillslope failure mechanisms can vary widely and the risks depend on a number of highly site-specific characteristics. Nevertheless, some studies have suggested that intense AR also have the potential to increase landslides (Mauger et al. 2015).

Sediment transport caused by erosion or landslides from upstream flooding has a number of impacts, including reservoir sedimentation, degraded water quality in streams and Puget Sound, regional carbon and nutrient cycling, and even amplification of downstream flood risks due to morphological changes (Nones 2019). Sea level rise and changes in coastal flooding could also have a significant impact on floodplain sediment transport and ecosystem dynamics, with enhanced saltwater intrusion (Yang et al. 2015). Sediment erosion and transport can be challenging to model due to the number of factors involved, but progress has been made in doing so in both Earth system models (e.g., Li et al. 2022; Tan et al. 2021) and higher resolution river models (Doten et al. 2006; Sun et al. 2016; HSCTM2D). The Puget Sound region would make an excellent testbed for examining sediment transport and landslides, and there has been a considerable amount of data collected to aid in model development, calibration, and validation, including one of the most comprehensive archives of landslide information in the United States (Department of Natural Resources Geologic Information Portal).

## 4.4 Droughts and Wildfires

While drought conditions are not as common in the Puget Sound basin as in some other regions, they do occur and can have profound implications due to the many regional systems that depend on water resources. The mechanisms that can lead to drought include warmer temperatures leading to less snowpack and/or higher evapotranspiration, persistent blocking high pressure ridges leading to less precipitation, and increases in local water stress due to surface-groundwater interactions and/or human management of water resources. The entire Pacific Northwest experienced record-breaking drought in 2015 that included an abnormally low snowpack (Figure 14), which in turn was driven by abnormally warm winter temperatures (Steel et al. 2019; Harpold et al. 2017). A more recent drought in 2021 followed by a heat wave led to most of the Pacific Northwest being under abnormally dry or drought conditions (Ansah and Walsh 2021). Droughts are typically associated with low summer river flows and unusually high water temperatures, which have major consequences for water supplies, salmonid species, agriculture, energy production, and ecosystem health.

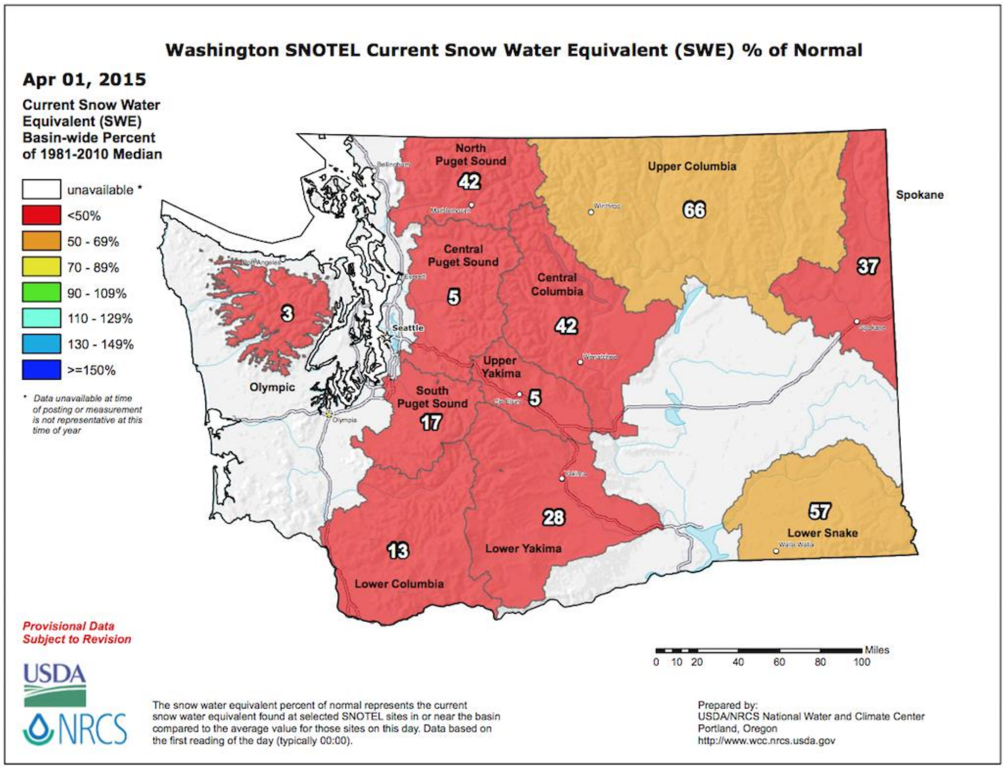


Figure 14. Map of Washington showing the snow drought (i.e., abnormally low level of snow water equivalent or SWE) on April 1, 2015. Source: USDA/NRCS.

The frequency and severity of droughts around Puget Sound are expected to increase with climate change, especially as increasing temperatures are combined with declines in spring snowpack and summer precipitation (River Management Joint Operating Committee 2018; Mauger et al. 2015; Hamlet et al. 2005). While it was rare historically, the conditions experienced in 2015 are expected to become typical by the mid-21st century (Marlier et al. 2017). Concurrent drought and heat wave conditions are also increasing due to climate change (Mazdiyasni and AghaKouchak 2015), and precipitation trends suggest that the frequency and intensity of hot-dry events will continue to increase (Bevacqua et al. 2022).

Despite significant work conducted on improving our understanding and ability to model large-scale interactions among temperature, precipitation, and topographic dynamics, the modeling of droughts of different types, how they might change, and how they may affect the coupled human-Earth system differently in the future still presents significant challenges. These challenges include, for example, the complexity of modeling snow droughts, aquifer storage response to droughts, and accounting for the many human actions that interact with natural hydrological system (e.g., dam operating rules, water demands and changes due to population growth and agricultural land expansion, forest management practices that influence snowpack, compliance with water rights and treaties, etc.). In addition, human management boundaries are often artificial and do not follow watershed boundaries or interactions across management scales, which is especially significant in a highly managed region where water availability impacts span large geographical areas and multiple jurisdictions. The ability to manage the challenges arising from increasing drought frequency and intensity, compound extreme events (concurrent heat wave and drought), and extreme events in rapid succession (e.g., drought followed by flood), were identified during the workshop as being important research gaps. It was also noted that there are several definitions of drought, including those based on precipitation thresholds, hydrologic methods, and energy needs. Clarifying the definitions of drought was identified as another gap.

Wildfire represents another relatively rare, yet potentially catastrophic process that can affect the Puget Sound region, especially the forested areas on the western slopes of the Cascade mountains (Stevens-Rumann and Morgan 2019). The region historically exhibits a 35- to 300-year wildfire frequency with low to moderate stand replacement severity. Forest management practices and development at the wildland-urban interface around the region have significantly increased the potential for large and catastrophic fires (Halofsky et al. 2018; Radeloff et al. 2018; Hammer et al. 2007). At the time of this writing (September 2022), two large wildfires have led to the evacuations of several communities, the closure of two of the three major highways connecting the Puget Sound region with eastern Washington, and the de-energizing of several transmission lines. Some analyses have suggested that wildfires in the region are likely to increase in the future with changes in climate, population, and land use (Stevens-Rumann and Morgan 2019; Zhong et al. 2021), but considerable uncertainties remain.

Workshop participants and external sources generally agreed that direct wildfire impacts and risks are probably of less concern around Puget Sound than for adjacent regions in the Pacific Northwest (e.g., First Street Foundation 2022b). That being said, many of the knowledge gaps that exist for understanding heat waves, extreme precipitation, and drought are similar to those that exist for understanding fire risk, and these processes are obviously linked. Additional needs for fire predictability—which were highlighted in more detail at the recent ICAMS (Interagency Council for Advancing Meteorological Services) Wildland Fire Workshops—include coupled modeling of weather, fire behavior, and the land surface. Puget Sound workshop participants also identified the need to better understand the impact of wildfire smoke, particularly its impact on human health and environmental health (Errett et al. 2019; Ball et al. 2021), because smoke from wildfires in adjacent regions often moves into the Puget Sound basin. While conceptually understood, smoke impacts on air quality have not been explored in a systematic way (see, e.g., NASEM 2022).

# 5.0 Key Research Opportunities for Modeling

The preceding sections have highlighted some of the complex Earth system processes and coupled human-Earth system dynamics that distinguish the Puget Sound region. The region's complex topography and geography, strong rural-to-urban gradients, and Pacific maritime climate make it a compelling testbed for advancing scientific understanding in a multiscale and multisystem context. While much has been learned about atmospheric, terrestrial, marine, and human systems across the Puget Sound region, including the potential impacts of climate change and different types of extreme events, many observational, modeling, and integration gaps remain. In this section, the scoping study author team has attempted to filter and distill the key knowledge, methodological, and data gaps identified by workshop participants and other contributors into research topics that are aligned with DOE/BER/EESM program interests. In doing so, we have attempted to focus on opportunities that would leverage and extend existing modeling tools and activities, and on topics that are also relevant to other regions.

Before describing specific research opportunities, however, it is useful to share one overarching observation by workshop participants regarding research opportunities in the Puget Sound region: the importance and value of engaging with regional partners and stakeholders. The Pacific Northwest is home to a large and engaged climate and global change science and practitioner community that includes universities, state and local governments, tribes, utilities, nongovernmental organizations, and the private sector. This community spans a wide range of expertise and interests motivated to pursue various aspects of fundamental and applied science challenges relevant to the region. Some members of the community focus on scientific discovery and the tools needed to make those discoveries, including co-production of knowledge, while others emphasize the information and capabilities needed to support effective decision-making. DOE is well positioned to leverage the strengths of both of these communities to advance knowledge in a use-inspired scientific framework. The HyperFACETS project has shown the value of engaging with local and regional stakeholder communities to guide scientific efforts, and there has been a renewed emphasis across many parts of DOE on the benefits of a "research-to-operations-to-research" paradigm for advancing knowledge. The Puget Sound region offers excellent opportunities to embrace this approach across the research areas described below.

## 5.1 Earth System Modeling Opportunities

The geographic context of Puget Sound and existing community strengths in modeling different components of the Earth system make it an ideal setting for enhancing the representation of key processes and interactions in numerical models. The workshop and literature review identified a number of specific areas in which improvements in regional and/or global Earth system models would be helpful for improving our ability to predict and project future changes in and around Puget Sound as well as in other regions. Many of these are centered on processes that involve topography, such as orographic precipitation and flooding driven by ARs and ROS, as well as on feedbacks between different system components of the natural and human-Earth system. There was also a strong sentiment for incorporating additional human system dynamics into Earth System models as an important area of focus. DOE's E3SM would be an obvious target for some of these enhancements; it has a non-hydrostatic atmosphere model, regional refinement capability, a land surface model that includes a subgrid hierarchical structure to represent subgrid heterogeneity, a radiative transfer scheme that represents topographic effects on solar radiation, an irrigation module and an urban canopy model, and a river routing model that already includes a basic representation of water management coupled with irrigation water demand.. Other processes, such as compound flooding along the complex Puget Sound shoreline or the inclusion of human decision-making across multiple systems and scales, would likely require coupling with other models. More detailed, limited-domain models could also help inform the development of certain processes in E3SM and other large-scale models, as would using a hierarchy of modeling constructs to evaluate E3SM performance. The following is a non-exhaustive list of some of the key topics of research DOE would be well positioned to lead:

- Improving the representation of subgrid heterogeneity in coastal regions with complex terrain and assessing its influence on atmospheric and terrestrial processes
- Representing the multiscale surface-atmosphere interactions that drive extreme temperature events, especially large-scale blocking events combined with the finer-scale resolution needed to resolve local temperature differences
- Processes that control the predictability of AR behavior, such as moisture transport, precipitation over the ocean, and freezing level in regions with complex topography
- Refined resolution and process representation for predicting snowpack dynamics and associated extreme events (e.g., ROS, snow drought), which is particularly difficult in Puget Sound due to its warm winter conditions interacting with complex topography
- Warm rain processes, interactions of rain with existing snowpack, and processes controlling ROS runoff
- Inclusion of additional time-varying urbanization processes in Earth system modeling frameworks to study its influence on local-to-regional climate, hydroclimate, radiative fluxes, flooding, drought, and other atmospheric and terrestrial processes
- Two-way surface-atmosphere feedbacks across urban-rural and topographic gradients, especially those involving snow and vegetation and associated with extreme events (e.g., ARs, ROS, droughts, and wildfire)
- Enhancing the representation of water management activities in ESMs, e.g., more dynamic reservoir operation rules and multisectoral water supply decision-making
- Representation of compound coastal flooding processes, including surface and groundwater interactions, floodplain and sea level interactions, and corresponding biogeochemical changes and impacts.

## 5.2 Regional Climate Simulation and Analysis Opportunities

Similarly, the unique features of the Puget Sound region offer a number of opportunities to advance our understanding of important Earth system processes through the design, evaluation, and analysis of numerical simulations and related observations. Some of the research gaps relevant to these activities are closely related to the model development opportunities noted above, while others represent areas in which existing data and/or modeling tools already have the potential to significantly advance scientific understanding of processes that occur across Puget Sound as well as other regions. Workshop participants noted a number of specific areas in which model intercomparisons, development of metrics and benchmarks, advanced statistical analyses, uncertainty characterization, and other methods could yield readily transferable scientific understanding of key processes in and interactions across atmospheric, terrestrial, and marine systems, including the following:

- Leverage or partner with HyperFACETS to evaluate optimal downscaling methods and products for representing specific Earth system processes or variables, and improving the characterization of uncertainties associated with downscaling approaches.
- Conduct experiments to understand the tradeoff between climate downscaling versus E3SM regional refinement in regions with complex geography.
- Use multi-model, multiscale ensemble simulations to isolate the impact of anthropogenic forcing versus internal variability on extreme events and related atmospheric circulation features such as ridging and blocking.
- Design and conduct novel experiments that help identify the initiation, evolution, and impact on local climate of extreme events such extreme temperature (e.g., blocking) and precipitation events (e.g., ARs).
- Design and conduct novel experiments to understand the mechanistic connections between extreme events and modes of climate variability and hence, predictability of extreme events at subseasonal-to-multi-decadal timescales.
- Develop storylines for extreme event attributions and projections of future changes in extreme events in the Puget Sound region.
- Develop a high-resolution land data assimilation product that includes natural processes and the impact of human systems.
- Couple watershed, coastal, and atmospheric models to better understand the processes of compound flooding events (e.g., the impact of AR winds), and how they evolve under different scenarios of sea level rise, climate change, land use land cover changes, and competing water management objectives.
- Use AI/ML and other analysis techniques to better understand the drivers of rain/snow transitions, especially in the context of complex terrain, the relationship between ARs and snowpack dynamics, and drivers and predictability of wildfires.
- Enhance understanding of the sensitivity of snowpack and ROS to forest alterations at different elevations and contexts.

## 5.3 Human and Human-Earth System Modeling Opportunities

Workshop participants repeatedly highlighted the need to improve the representation of human systems in Earth and environmental systems models, as well as the need to develop more complete and detailed modeling approaches for a variety of relevant human systems. These same research gaps exist in many regions around the world, but the research community around Puget Sound would be particularly well suited to addressing a number of key systems and interactions, including forest management, urban science, transportation infrastructure, building science, the electric grid, economics, water management, human and environmental health, and the impacts of climate and other global changes on under-represented communities. Building on recent work in the MultiSector Dynamics community (Yoon et al. 2022), workshop participants also suggested that it would be helpful to develop a typology of human system processes and interactions with regional Earth systems to help identify and target missing or under-represented processes and interactions more comprehensively. This typology would be extremely useful for prioritizing specific model developments, coupling approaches, and data needs, and would also help to connect domain knowledge gaps with specific human system impacts, decisions, and societal benefits—all of which would help enable a true “research-to-operations-to-research" paradigm. The following were some of the specific research activities identified during the scoping study:

- Simulate drivers of regional population changes and how these drivers might change in future decades under different socioeconomic, policy, and climate scenarios.
- Clarify the forces and factors controlling urban and regional development patterns, along with the attendant land use and land cover changes.
- Link local-scale forest management decisions with regional policies and regulations and with global human and Earth system changes (e.g., economics, carbon dioxide levels) to better understand the drivers and land use and land cover consequences.
- Understand historical and projecting future changes in water resources under different scenarios of hydrologic changes and human use, especially in heavily managed watersheds experiencing snow-to-rain transitions.
- Represent the influence of humans on the terrestrial-aquatic interface across urban-to-rural contexts, including shoreline modification and sediment transport, runoff and water quality, use of green flood control measures, etc.
- Develop modeling approaches to connect different human systems (e.g., population trends, urbanization, buildings, energy, and transportation) at local-to-regional scales.
- Improve the representation of human decision-making at different scales and across linked systems, including factors that drive or influence decision-making (e.g., culture, perceptions, values, decision-making, institutions, authority, etc.).
- Use AI/ML approaches to leverage existing data sets to better understand the behavior of specific human systems (e.g., energy use, healthcare, etc.) as well as connectivity between them.
- Explore new methods to generate and evaluate integrated scenarios and storylines, including large ensembles of exposure scenarios to better understand risk profiles, ML-based scenario discovery approaches, and outcome-oriented metrics.
- Develop new approaches to model multiple dimensions of human well-being and using these approaches to understand the vulnerabilities and risks associated with different segments of the population.

## 5.4 Cross-cutting Needs and Collaboration Opportunities

In addition to identifying research that would be aligned with the strategic aims of DOE's EESM program, scoping study participants identified additional science gaps that could potentially be filled by other BER programs, other parts of DOE, other federal agencies, or various state and local groups. The ideas listed below thus represent opportunities to build cross-programmatic and cross-institutional resources and collaborations that would complement potential DOE/EESM-funded efforts in the region.

- Acquire additional atmospheric observations and surface data for developing, calibrating, and validating models, including data on AR precipitation amount/type, snowpack, and soil moisture. This might include, for example, an Atmospheric Radiation Measurement (ARM) campaign focused on the snow-rain transition zone.
- Leverage and build additional data on water quality in and around Puget Sound, especially during and after flooding events.

- Leverage and build connections with urban planning and infrastructure data and modeling efforts to better understand how water and energy systems are connected to regional transportation, communication, supply chains, land use, etc.
- Partner with organizations aimed at better understanding climate impacts in the Puget Sound region, including impacts on different communities and segments of the population, to better understand and simulate vulnerabilities, risks, and potential adaptation approaches.
- Develop improved understanding and ability to model landslide risks, including how the risks might be changing due to climate change and other factors.
- Understand potential synergies between geologic hazard preparedness and climate adaptation efforts.
- Engage with agencies involved in human and environmental health to improve understanding and ability to simulate impacts of wildfire smoke, degraded air and water quality, and other ongoing changes in the region.
- Partner with “big data” organizations around Puget Sound to develop and/or leverage novel analytic methods with non-traditional observations such as cell phone data and even citizen science to help better understand human systems.
- Conduct joint modeling exercises that engage multiple teams across organizations and programs; for example, through the use of coordinated and tailored scenarios and storylines.
- Improve representation of fire predictability through coupled modeling of weather, fire behavior, and the land surface.
- Support efforts aimed at making data discoverable, sharable, and interoperable.

## 6.0 References

*The list below contains works cited in this report. A complete list of references compiled throughout the scoping study is available here.*

Alberti, M., R. Weeks, and S. Coe. 2004. Urban land-cover change analysis in central Puget Sound. Photogrammetric Engineering & Remote Sensing, 70(9), 1043-1052.

Alberti, M. and M. Bidwell. 2005. Assessing the impacts of urbanization on shellfish growing areas in Puget Sound. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.454.636&rep=rep1&type=pdf

Alberti, M. and J. M. Marzluff. 2004. Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. Urban ecosystems, 7(3), 241-265.

Ansah, E.O. and O. S. Walsh. 2021. Impact of 2021 Drought in the Pacific Northwest. Crops & Soils Magazine, 54, 46-49. doi: 10.1002/crso.20145

Arnold, L., M. D. Scheuerell, and T. Busch Isaksen. 2022. Mortality associated with extreme heat in Washington State: The historical and projected public health burden. Atmosphere, 13, 1392. doi: 10.3390/atmos13091392

Ball, G., P. Regier, R. González-Pinzón, J. Reale, and D. Van Horn. 2021. Wildfires increasingly impact western US fluvial networks. Nature Communications, 12(1), 2484. doi: 10.1038/s41467-021-22747-3

Balling, R. C., and G. B. Goodrich. 2011. Spatial analysis of variations in precipitation intensity in the USA. Theoretical and Applied Climatology, 104, 415-421. doi: 10.1007/s00704-010-0353-0

Bevacqua, E., G. Zappa, F. Lehner, and J. Zscheischler. 2022. Precipitation trends determine future occurrences of compound hot–dry events. Nature Climate Change, 12(4), 350-355. doi: 10.1038/s41558-022-01309-5

Biedenweg, K., D. J. Trimbach, W. Fleming. 2021. Integrating social science in Puget Sound restoration. Ecological Restoration, 39(4), 226-237. doi: 10.3368/er.39.4.226

Biedenweg, K. 2017. A comparative study of human well-being indicators across three Puget Sound regions. Society & Natural Resources, 30(3), 362-376. doi: 10.1080/08941920.2016.1209606

Binder, L., and J. Morse. 2016. Climate resilient floodplains: Local perspectives on integrating climate resilience into watershed planning in the Stillaguamish and Puyallup River watersheds. Retrieved from https://cig.uw.edu/wp-content/uploads/sites/2/2021/06/Integrating-Climate-Resilience-in-Puget-Sound-Floodplain-and-Working-Lands-Programs_Interviews.pdf

Bond, N. A. 2021. The Blob. In State of the Salish Sea, 134-135. Salish Sea Institute, Western Washington University.

Bowling, L. C., P. Storck, and D. P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. Water Resources Research, 36, 3223-3240.

Brandenberger, J. M., P. Louchouarn, and E. A. Crecelius. 2011. Natural and post-urbanization signatures of hypoxia in two basins of Puget Sound: Historical reconstruction of redox sensitive metals and organic matter inputs. Aquatic Geochemistry, 17, 645-670. doi: 10.1007/s10498-011-9129-0

Bryan, S. 2021. The Pacific Northwest could be a ‘climate refuge’. https://www.king5.com/article/entertainment/television/programs/evening/the-pacific-northwest-could-be-a-climate-refuge/281-463125827

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(7, 1618-1631. doi: 10.1175/jamc-d-12-094.1

Caldwell, P. M., C. R. Terai, B. Hillman, N. D. Keen, P. Bogenschutz, W. Lin. 2021. Convection-permitting simulations with the E3SM global atmosphere model. Journal of Advances in Modeling Earth Systems, 13, e2021MS002544. doi: 10.1029/2021MS002544

Cannon, F., F. M. Ralph, A. M. Wilson, and D. P. Lettenmaier. 2017. GPM satellite radar measurements of precipitation and freezing level in atmospheric rivers: Comparison with ground-based radars and reanalyses. Journal of Geophysical Research: Atmospheres 122(23), 12,747-12,764. doi: 10.1002/2017JD027355

Cao, Q., A. Gershunov, T. Shulgina, F. Martin Ralph, N. Sun, and D. P. Lettenmaier. 2020. "Floods due to atmospheric rivers along the U.S. west coast: The role of antecedent soil moisture in a warming climate." Journal of Hydrometeorology 21 (8):1827-1845. doi: 10.1175/JHM-D-19-0242.1

Cao, Q., N. Sun, J. Yearsley, B. Nijssen, and D. P. Lettenmaier. 2016. Climate and land cover effects on the temperature of Puget Sound streams. Hydrological Processes, 30(13), 2286-2304. doi:10.1002/hyp.10784

Chandra-Putra, H., C. J. Andrews. 2020. An integrated model of real estate market responses to coastal flooding. Journal of Industrial Ecology, 24, 424-435. doi: 10.1111/jiec.12957

Chen, X., and L. R. Leung. 2020. Response of landfalling atmospheric rivers on the U.S. West Coast to local sea surface temperature perturbations. Geophysical Research Letters, 47(18), e2020GL089254. doi: 10.1029/2020GL089254

Chen, X., L. R. Leung, Y. Gao, Y. Liu, M. Wigmosta, and M. Richmond. 2018. Predictability of extreme precipitation in western U.S. watersheds based on atmospheric river occurrence, intensity, and duration. Geophysical Research Letters, 45, 11,693-11,701. doi: 10.1029/2018GL079831

Clark, M. P., J. Hendrikx, A. G. Slater, D. Kavetski, B. Anderson, N. J. Cullen, T. Kerr, E. Örn Hreinsson, and R. A. Woods. 2011. Representing spatial variability of snow water equivalent in hydrologic and land-surface models: A review. Water Resources Research, 47, W07539. doi:10.1029/2011WR010745

Climate Impacts Group, UW Department of Environmental and Occupational Health Sciences, Front and Centered and Urban@UW. 2018. An Unfair Share: Exploring the disproportionate risks from climate change facing Washington state communities. A report prepared for Seattle Foundation. University of Washington, Seattle. https://cig.uw.edu/wp-content/uploads/sites/2/2018/08/AnUnfairShare_WashingtonState_August2018.pdf

Community Coordinating Group on Integrated Hydro-Terrestrial Modeling. 2020. Integrated Hydro-Terrestrial Modeling: Development of a National Capability. Report from an interagency workshop held September 4-6, 2019 with support from the National Science Foundation, the U.S. Department of Energy, and the U.S. Geological Survey. doi: 10.25584/09102020/1659275

Copping, A., Z. Yang, I. Miller, J. Apple, G. Mauger, N. Voisin, A. Fullerton, N. Sun, and M. Freeman. 2018. Providing modeling tools on extreme events of climate change to Puget Sound managers. Salish Sea Ecosystem Conference, Seattle, WA.

Cuo, L., T. K. Beyene, N. Voisin, F. Su, D. P. Lettenmaier, M. Alberti, and J. E. Richey. 2011. Effects of mid-twenty-first century climate and land cover change on the hydrology of the Puget Sound basin, Washington. Hydrological Processes, 25(11), 1729-1753.

Cuo, L., D. P. Lettenmaier, M. Alberti, and J. E. Richey. 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes: An International Journal, 23(6), 907-933.

Currier, W. R., and J. D. Lundquist. 2018. Snow depth variability at the forest edge in multiple climates in the western United States. Water Resources Research, 54, 8756-8773. doi: 10.1029/2018WR022553

D'Aquila, S. 2022. The legacy of redlining and the disproportionate exposure to extreme heat in Seattle, Washington. Master's Thesis. http://hdl.handle.net/1773/49460.

de Chalendar, J. A., J. Taggart, and S. M. Benson. 2019. Tracking emissions in the US electricity system. Proceedings of the National Academy of Sciences, 116(51), 25497-25502. doi: 10.1073/pnas.1912950116

Déry, S. J., M. A. Hernández-Henríquez, T. A. Stadnyk, and T. J. Troy. 2021. Vanishing weekly hydropeaking cycles in American and Canadian rivers. Nature Communications, 12(1), 7154. doi: 10.1038/s41467-021-27465-4

Dettinger, M. D. 2013. Atmospheric rivers as drought busters on the U.S. West Coast. Journal of Hydrometeorology, 14(6), 1721-1732. doi: 10.1175/JHM-D-13-02.1

Department of Energy (DOE). 2017. Research priorities to incorporate terrestrial-aquatic interfaces in earth system models: workshop report, DOE/SC-0187, U.S. Department of Energy Office of Science. https://ess.science.energy.gov/tai-workshop/

Doten, C. O., L. C. Bowling, J. S. Lanini, E. P. Maurer, and D. P. Lettenmaier. 2006. A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds, Water Resources Research, 42(4), W04417 doi:10.1029/2004WR003829

Earth's Future. 2022. Modeling multisector dynamics to inform adaptive pathways. Special Issue of Earth's Future. https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2328-4277.ADTPATH1

Energy Information Administration (EIA). 2022. Washington State Energy Profile. https://www.eia.gov/state/print.php?sid=WA

Ekblad, L. and J. D. Herman. 2021. Toward data-driven generation and evaluation of model structure for integrated representations of human behavior in water resources systems. Water Resources Research, 57(2), e2020WR028148. doi: 10.1029/2020WR028148

Energy + Environmental Economics (E3). 2019. Resource Adequacy in the Pacific Northwest. https://www.ethree.com/wp-content/uploads/2019/03/E3_Resource_Adequacy_in_the_Pacific-Northwest_March_2019.pdf

Environment Canada, and U.S. Environment Protection Agency. 2014. The Georgia Basin-Puget Sound Airshed Characterization Report. https://www.canada.ca/en/environment-climate-change/services/air-pollution/publications/georgia-basin-puget-sound-report-2014.html

Errett, N. A., H. A. Roop, C. Pendergrast, B. Kramer, A. Doubleday, K. A. Tran, and T. Busch Isaksen. 2019. Building a practice-based research agenda for wildfire smoke and health: a report of the 2018 Washington Wildfire Smoke Risk Communication Stakeholder Synthesis Symposium. International Journal of Environmental Research and Public Health, 16(13), 2398. doi: 10.3390/ijerph16132398

Espinoza, V., D. E. Waliser, B. Guan, D. A. Lavers, and F. M. Ralph. 2018. Global analysis of climate change projection effects on atmospheric rivers. Geophysical Research Letters, 45, 4299-4308. doi: 10.1029/2017GL076968

Feely, R. A., S. R. Alin, J. Newton, C. L. Sabine, M. Warner, A. Devol, C. Krembs, C. Maloy. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. Estuarine, Coastal and Shelf Science, 88(4), 442-449. doi: 10.1016/j.ecss.2010.05.004

Feifel, K. and K. N. Braddock. 2021. Planning for sea level rise in Olympia, Washington [Case study on a project of the City of Olympia's Public Works Department]. Version 2.0. Product of EcoAdapt's State of Adaptation Program. Retrieved from CAKE: https://www.cakex.org/case-studies/planning-sea-level-rise-olympia-washington

First Street Foundation. 2022a. The 6th National Risk Assessment: Hazardous Heat. https://report.firststreet.org/heat

First Street Foundation. 2022b. The 5th National Risk Assessment: Fueling the Flames. https://report.firststreet.org/

Fullerton, A. H., N. Sun, M. J. Baerwalde, B. L. Hawkins, and H. Yan. 2022, Mechanistic simulations suggest riparian restoration can partly counteract climate impacts to juvenile salmon. Journal of the American Water Resource Association, 58, 525-546. doi: 10.1111/1752-1688.13011

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 (17), 7179-7186. doi: 10.1002/2015GL065435

Garrison-Laney, C. and I. Miller. 2017. Tsunamis in the Salish Sea: Recurrence, sources, hazards. The Puget lowland to east of the Cascade range: geologic excursions in the Pacific Northwest. Geological Society of America Field Guide, 49, 67-78.

Gershunov, A., T. Shulgina, F. M. Ralph, D. A. Lavers, and J. J. Rutz. 2017. Assessing the climate-scale variability of atmospheric rivers affecting western North America. Geophysical Research Letters, 44, 7900-7908. doi: 10.1002/2017GL074175

Gibbons, D. R. and E. O. Salo. 1973. an annotated bibliography of the effects of logging on fish of the western United States and Canada. Retrieved from https://www.fs.usda.gov/treesearch/pubs/22556

Goldenson, N., L. R. Leung, C. M. Bitz, and E. Blanchard-Wrigglesworth. 2018. Influence of atmospheric rivers on mountain snowpack in the western United States. Journal of Climate, 31(24), 9921-9940. doi: 10.1175/JCLI-D-18-0268.1

Grotjahn, R., R. Black, R. Leung, M. F. Wehner, M. Barlow, M. Bosilovich, A. Gershunov, W. J. Gutowski, J. R. Gyakum, R. W. Katz, Y. Lee, Y. Lim, and Prabhat. 2016. North American extreme temperature events and related large scale meteorological patterns: a review of statistical methods, dynamics, modeling, and trends. Climate Dynamics, 46(3), 1151-1184. doi: 10.1007/s00382-015-2638-6

Gutmann, E., T. Pruitt, M. P. Clark, L. Brekke, J. Arnold, D. A. Raff, and R. M. Rasmussen. 2014. An intercomparison of statistical downscaling methods used for water resource assessments in the United States. Water Resources Research, 50(9), 7167-7186. doi: 10.1002/2014WR015559

Hagos, S. M., L. R. Leung, J. H. Yoon, J. Lu, and Y. Gao. 2016. A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. Geophysical Research Letters, 43, 1357-1363. doi:10.1002/2015GL067392

Hallegatte, S., J. Hourcade, and P. Dumas. 2007. Why economic dynamics matter in assessing climate change damages: Illustration on extreme events. Ecological Economics, 62(2), 330-340. doi: https://doi.org/10.1016/j.ecolecon.2006.06.006

Halofsky, J. S., D. R. Conklin, D. C. Donato, J. E. Halofsky, J. B. Kim. 2018. Climate change, wildfire, and vegetation shifts in a high-inertia forest landscape: Western Washington, U.S.A. PLOS ONE, 13(12): e0209490. doi: 10.1371/journal.pone.0209490

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. Journal of Climate, 18, 4545-4561.

Hamman, J. J. 2012. Effects of projected twenty-first century sea level rise, storm surge, and river flooding on water levels in Puget Sound floodplains and estuaries." M.S., Civil and Environmental Engineering, University of Washington.

Hammer, R. B., V. C. Radeloff, J. S. Fried, S. I. Stewart. 2007, Wildland–urban interface housing growth during the 1990s in California, Oregon, and Washington. International Journal of Wildland Fire, 16, 255-265. doi: 10.1071/WF05077

Hanna, R., and J. Marqusee. 2022. Designing resilient decentralized energy systems: The importance of modeling extreme events and long-duration power outages. iScience, 25(1), 103630. doi: 10.1016/j.isci.2021.103630.

Harpold, A. A., M. Dettinger, and S. Rajagopal. 2017. Defining snow drought and why it matters. Eos, Earth and Space Science News, 98. doi: 10.1029/2017EO068775

Hepinstall-Cymerman, J., S. Coe, S. and L. R. Hutyra. 2013. Urban growth patterns and growth management boundaries in the Central Puget Sound, Washington, 1986–2007. Urban Ecosystems, 16, 109-129. doi: 10.1007/s11252-011-0206-3

Hu, J. M., and A. W. Nolin. 2019. Snowpack contributions and temperature characterization of landfalling atmospheric rivers in the Western Cordillera of the United States. Geophysical Research Letters, 46, 6663-6672. doi: 10.1029/2019GL083564

Huang, X., A. M. Rhoades, P. A. Ullrich, and C. M. Zarzycki. 2016. An evaluation of the variable-resolution-CESM for modeling California's climate, Journal of Advances in Modeling Earth Systems, 8, 345-369. doi: 10.1002/2015MS000559

Huang, X., D. L. Swain, D. B. Walton, S. Stevenson, and A. D. Hall. 2020. Simulating and Evaluating Atmospheric River-Induced Precipitation Extremes Along the U.S. Pacific Coast: Case Studies From 1980–2017. Journal of Geophysical Research: Atmospheres 125(4). doi: 10.1029/2019JD031554

Jiang, Y., J. B. Kim, C. J. Still, B. K. Kerns, J. D. Kline, and P. G. Cunningham. 2018. Inter-comparison of multiple statistically downscaled climate datasets for the Pacific Northwest, USA. Scientific Data, 5(1), 180016. doi: 10.1038/sdata.2018.16

Karlin, R. E., M. Holmes, S. E. B. Abella, and R. Sylwester. 2004. Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington. Geological Society of America Bulletin, 116(1-2), 94-108.

Kern, J. D., Characklis, G. W., Doyle, M. W., Blumsack, S. and Whisnant, R. B. 2012. Influence of deregulated electricity markets on hydropower generation and downstream flow regime. Journal of Water Resources Planning and Management, 138(4), 342-355.

Khangaonkar, T., Nugraha, A., Yun, S. K., Premathilake, L., Keister, J. E., and Bos, J. 2021. Propagation of the 2014–2016 northeast Pacific marine heatwave through the Salish Sea. Frontiers in Marine Science, 8. doi: 10.3389/fmars.2021.787604

Klein, T., J. M. Torres-Ruiz, and J. J. Albers. 2022. Conifer desiccation in the 2021 NW heatwave confirms the role of hydraulic damage. Tree Physiology. doi: 10.1093/treephys/tpac007

Kyle, G. P., Luckow, P., Calvin, K. V., Emanuel, W. R., Nathan, M., and Zhou, Y. 2011. GCAM 3.0 Agriculture and Land Use: Data Sources and Methods. doi: 10.2172/1036082

L'Ecuyer, T. S., H. K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, C. A. Clayson, E. Wood, J. Sheffield, R. Adler, G. Huffman, M. Bosilovich, G. Gu, F. Robertson, P. R. Houser, D. Chambers, J. S. Famiglietti, E. Fetzer, W. T. Liu, X. Gao, C. A. Schlosser, E. Clark, D. P. Lettenmaier, and K. Hilburn. 2015. The observed state of the energy budget in the early twenty-first century. Journal of Climate, 28(21), 8319-8346. doi: 10.1175/jcli-d-14-00556.1

Lee, S., A. H. Fullerton, N. Sun, and C. E. Torgersen. 2020. Projecting spatiotemporally explicit effects of climate change on stream temperature: A model comparison and implications for coldwater fishes. Journal of Hydrology, 588, 125066. doi: 10.1016/j.jhydrol.2020.125066

Lee, S. Y., A. F. Hamlet, and E. Grossman. 2016. impacts of climate change on regulated streamflow, flood control, hydropower production, and sediment discharge in the Skagit River Basin. Northwest Science, 90(1), 23-43. doi: 10.3955/046.090.0104

Leung, L. R., and Y. Qian. 2003. Changes in seasonal and extreme hydrologic conditions of the Georgia Basin/Puget Sound in an ensemble regional climate simulation for the mid-century. Canadian Water Resources Journal, 28(4), 605-631. doi: 10.4296/cwrj2804605

Li, D., Lettenmaier, D. P., Margulis, S. A., and Andreadis, K. 2019. The role of rain-on-snow in flooding over the conterminous United States. Water Resources Research, 55, 8492-8513. doi: 10.1029/2019WR024950

Liu, P., Reed, K. A., Garner, S. T., Zhao, M., and Zhu, Y. 2022. Blocking simulations in GFDL GCMs for CMIP5 and CMIP6. Journal of Climate, 35(15), 5053-5070. doi: 10.1175/JCLI-D-21-0456.1

Marchau, V. A., Walker, W. E., Bloemen, P. J. and Popper, S. W. 2019. Decision making under deep uncertainty: from theory to practice (p. 405). Springer Nature.

Marlier, M. E., M. Xiao, R. Engel, B. Livneh, J. T. Abatzoglou, and D. P. Lettenmaier. 2017. The 2015 drought in Washington State: a harbinger of things to come? Environmental Research Letters, 12(11), 114008. doi: 10.1088/1748-9326/aa8fde

Mauger, G., Liu, M., Adam, J., Won, J., Wilhere, G., Dulan, D., Atha, J., Helbrecht, L., and Quinn, T. 2021. New culvert projections for Washington State: Improved modeling, probabilistic projections, and an updated web tool. Climate Impacts Group, University of Washington.

Mauger, G., S. Lee, C. Bandaragoda, Y. Serra, and J. Won. 2016. Effect of climate change on the hydrology of the Chehalis Basin. Climate Impacts Group, University of Washington.

Mauger, G., J. Casola, H. Morgan, R. Strauch, B. Jones, B. Curry, T. Busch Isaksen, L. Whitely Binder, M. Krosby, and A. Snover. 2015. State of knowledge: Climate change in Puget Sound. Climate Impacts Group, University of Washington.

Mazdiyasni, O., and A. AghaKouchak. 2015. Substantial increase in concurrent droughts and heatwaves in the United States. Proceedings of the National Academy of Sciences, 112(37), 11484-11489. doi: 10.1073/pnas.1422945112

Mendoza, P. A., Rajagopalan, B., Clark, M. P., Ikeda, K., and Rasmussen, R. M. 2015. Statistical postprocessing of high-resolution regional climate model output. Monthly Weather Review, 143(5), 1533-1553.

McCabe, G. J., M. P. Clark, and L. E. Hay. 2007. Rain-on-snow events in the Western United States. Bulletin of the American Meteorological Society, 88(3), 319-328. doi: 10.1175/bams-88-3-319.

Miller, I., H. Morgan, G. Mauger, T. Newton, R. Weldon, D. Schmidt, M. Welch, and E. Grossman. 2018. projected sea level rise for Washington State - A 2018 assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey.

Milman, O. 2021. ‘Nowhere is safe’: heat shatters vision of Pacific north-west as climate refuge. https://www.theguardian.com/us-news/2021/jul/21/pacific-northwest-heatwave-dome-climate-change

Moon, S., C. Page Chamberlain, K., Blisniuk, N. Levine, D. H. Rood, and G. E. Hilley. 2011. Climatic control of denudation in the deglaciated landscape of the Washington Cascades. Nature Geoscience, 4, 469–473. doi: 10.1038/ngeo1159

Moore, S. K., N. J. Mantua, J. P. Kellogg, and J. A. Newton. 2008. Local and large-scale climate forcing of Puget Sound oceanographic properties on seasonal to interdecadal timescales. Limnology and Oceanography, 53(5), 1746-1758. doi: 10.4319/lo.2008.53.5.1746.

Moore, S. K., Johnstone, J. A., Banas, N. S. and Salathe Jr, E. P. 2015. Present-day and future climate pathways affecting Alexandrium blooms in Puget Sound, WA, USA. Harmful Algae, 48, 1-11. doi: 10.1016/j.hal.2015.06.008

Moscrip, A. L. and D. R. Montgomery. 1997. Urbanization, flood frequency, and salmon abundance in Puget lowland streams. Journal of the American Water Resources Association, 33, 1289-1297.

Moss, R. H., Meehl, G. A., Lemos, M. C., Smith, J. B., Arnold, J. R., Arnott, J. C Wilbanks, T. J. 2013. Hell and High Water: Practice-Relevant Adaptation Science. Science, 342(6159), 696-698. doi:10.1126/science.1239569

Mote, P. W. 2003. Trends in temperature and precipitation in the Pacific Northwest during the twentieth century. Northwest Science, 77(4), 271-282.

Mote, P. W., S. Li, D,. P. Lettenmaier, M. Xiao, and R. Engel. 2018. Dramatic declines in snowpack in the western US. Climate and Atmospheric Science 1(1), 2. doi: 10.1038/s41612-018-0012-1

Musselman, K. N., Lehner, F., Ikeda, K. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. Nature Climatic Change, 8, 808-812. doi: 10.1038/s41558-018-0236-4

National Academies of Science, Engineering and Medicine (NASEM). 2022. Wildland fires: toward improved understanding and forecasting of air quality impacts. https://nap.nationalacademies.org/catalog/26465/wildland-fires-toward-improved-understanding-and-forecasting-of-air-quality-impacts

National Climate Assessment, 2014. Retrieved from https://nca2014.globalchange.gov/report

National Climate Assessment, 2018. Retrieved from https://nca2018.globalchange.gov/

Newton, T. J., Weldon, R., Miller, I. M., Schmidt, D., Mauger, G., Morgan, H. and Grossman, E., 2021. An assessment of vertical land movement to support coastal hazards planning in Washington State. Water, 13(3), 281.

Nones, M. 2019. Dealing with sediment transport in flood risk management. Acta Geophysica, 67, 677-685. doi: 10.1007/s11600-019-00273-7

Northwest Indian Fisheries Council (NWIFC). 2014. Understanding tribal treaty rights in western Washington. https://nwifc.org/w/wp-content/uploads/downloads/2014/10/understanding-treaty-rights-final.pdf

Philip, S. Y., S. F. Kew, G. J. van Oldenborgh, F. S. Anslow, S. I. Seneviratne, R. Vautard, D. Coumou, K. L. Ebi, J. Arrighi, R. Singh, M. van Aalst, C. Pereira Marghidan, M. Wehner, W. Yang, S. Li, D. L. Schumacher, M. Hauser, R. Bonnet, L. N. Luu, F. Lehner, N. Gillett, J. Tradowsky, G. A. Vecchi, C. Rodell, R. B. Stull, R. Howard, and F. E. L. Otto. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. Earth System Dynamics 2021, 1-34. doi: 10.5194/esd-2021-90

Polebitski, A. S., Palmer, R. N. and Waddell, P. 2011. Evaluating water demands under climate change and transitions in the urban environment. Journal of Water Resources Planning and Management, 137(3), 249-257.

Policygenius. 2022. The best and worst cities for climate change in 2022. https://www.policygenius.com/homeowners-insurance/best-and-worst-cities-climate-change/

Puget Sound Energy (PSE). 2022. Energy Sources. https://www.pse.com/en/pages/energy-supply/

Puget Sound National Estuary Program. 2020. Project Spotlight: High Resolution Change Detection. Retrieved from https://pugetsoundestuary.wa.gov/2020/10/07/hrcd_update2020/

Qian, Y., T. Chakraborty, J. Li, D. Li, C. He, C. Sarangi, F. Chen, X. Yang, and L. Leung. 2022. Urbanization impact on regional climate and extreme weather: current understanding, uncertainties, and future research directions. Advances in Atmospheric Sciences, 39, 819-860. doi: 10.1007/s00376-021-1371-9

Quinn, T. 2010. An environmental and historical overview of the Puget Sound ecosystem, in Shipman, H., Dethier, M. N., Gelfenbaum, G., Fresh, K. L., and Dinicola, R. S., eds., 2010, Puget Sound shorelines and the impacts of armoring—proceedings of a state of the science workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 11-18.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A. Stewart, S. I. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences, 115(13), 3314-3319. doi: 10.1073/pnas.1718850115

Raleigh, M. S., B. Livneh, K. Lapo, and J. D. Lundquist. 2016. How does availability of meteorological forcing data impact physically based snowpack simulations? Journal of Hydrometeorology, 17(1), 99-120. doi: 10.1175/jhm-d-14-0235.1

Raymond, W. W., Barber, J. S., Dethier, M. N., Hayford, H. A., Harley, C. D. G., King, T. L., Paul, B. 2022. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. Ecology, 103(10), e3798. doi: 10.1002/ecy.3798

Raymond, C., Conway-Cranos, L., Morgan, H., Faghin, N., Spilsbury Pucci, D., Krienitz, J., Miller, I., Grossman, E. and Mauger, G. 2018. Sea level rise considerations for nearshore restoration projects in Puget Sound. A report prepared for the Washington Coastal Resilience Project. https://cig.uw.edu/publications/sea-level-rise-considerations-for-nearshore-restoration-projects-in-puget-sound/

Reed, P. M., Hadjimichael, A., Moss, R. H., Monier, E., Alba, S., Brelsford, C., Burleyson, C., Cohen, S., Dyreson, A., Gold, D., Gupta, R., Keller, K., Konar, M., Macknick, J., Morris, J., Srikrishnan, V., Voisin, N., and Yoon, J. 2022. MultiSector Dynamics: Scientific challenges and a research vision for 2030, A community of practice supported by the United States Department of Energy's Office of Science. doi: 10.5281/zenodo.6144309

Rhoades, A. M., Jones, A. D., Srivastava, A., Huang, H., O'Brien, T. A., Patricola, C. M. 2020. The shifting scales of western U.S. landfalling atmospheric rivers under climate change. Geophysical Research Letters, 47, e2020GL089096. doi: 10.1029/2020GL089096

River Management Joint Operating Committee. 2018. Climate and Hydrology datasets for RMJOC long-term planning studies: second edition. Part I: Hydroclimate projections and analyses. Retrieved from https://www.bpa.gov/-/media/Aep/power/hydropower-data-studies/rmjoc-ll-report-part-l.pdf

Rosenberg, E. A., Keys, P. W., Booth, D. B., Hartley, D., Burkey, J., Steinemann, A. C. and Lettenmaier, D. P. 2010. Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. Climatic Change, 102(1), 319-349.

Ruckelshaus, M. H., and M. M. McClure, coordinators. 2007. Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound ecosystem. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center. Seattle, Washington. 93 p.

Rutz, J. J., W. J. Steenburgh, and F. M. Ralph. 2014. Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. Monthly Weather Review, 142(2), 905-921. doi: 10.1175/MWR-D-13-00168.1

Ryoo, J. M., D. E. Waliser, D. W. Waugh, S. Wong, E. J. Fetzer, and I. Fung. 2015. Classification of atmospheric river events on the U.S. West coast using a trajectory model. Journal of Geophysical Research, 120(8), 3007-3028. doi: 10.1002/2014JD022023

Santella, N., L. J. Steinberg, and K. Parks. 2009. Decision making for extreme events: modeling critical infrastructure interdependencies to aid mitigation and response planning. Review of Policy Research, 26(4), 409-422. doi: 10.1111/j.1541-1338.2009.00392.x.

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.

Scott, K. M., Vallance, J. W., and Pringle, P. T. 1995. Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington. Retrieved from http://pubs.er.usgs.gov/publication/pp1547

Scott, D. N. and Collins, B. D. 2021. Frequent mass movements from glacial and lahar terraces, controlled by both hillslope characteristics and fluvial erosion, are an important sediment source to Puget sound rivers. Water Resources Research, 57(4), p.e2020WR028389. doi: 10.1029/2020WR028389

Sheridan, S. C., and C. C. Lee. 2018. Temporal trends in absolute and relative extreme temperature events across North America. Journal of Geophysical Research: Atmospheres, 123(21), 11,889-11,898. doi: 10.1029/2018JD029150

Shields, C. A., Rutz, J. J., Leung, L.-Y., Ralph, F. M., Wehner, M., Kawzenuk, B., Lora, J. M., McClenny, E., Osborne, T., Payne, A. E., Ullrich, P., Gershunov, A., Goldenson, N., Guan, B., Qian, Y., Ramos, A. M., Sarangi, C., Sellars, S., Gorodetskaya, I., Kashinath, K., Kurlin, V., Mahoney, K., Muszynski, G., Pierce, R., Subramanian, A. C., Tome, R., Waliser, D., Walton, D., Wick, G., Wilson, A., Lavers, D., Prabhat, Collow, A., Krishnan, H., Magnusdottir, G., and Nguyen, P. 2018. Atmospheric River Tracking Method Intercomparison Project (ARTMIP): project goals and experimental design, Geosciences Model Development, 11, 2455-2474. doi: 10.5194/gmd-11-2455-2018

Simpson, D. P. 2012. City of Olympia engineered response to sea level rise. Technical report prepared by Coast Harbor Engineering for the City of Olympia, Public Works Department, Planning and Engineering.

Smith, S. 2012. Controls on large and very large submarine landslides in Puget Sound, WA, USA: ProQuest Dissertations Publishing.

Snover, A. K., P. W. Mote, L. Whitely Binder, A. F. Hamlet, and N. J. Mantua. 2005. Uncertain future: climate change and its effects on Puget Sound. A report for the Puget Sound Action Team by the Climate Impacts Group, University of Washington, Seattle.

Stark, T. D., A. K. Baghdady, O. Hungr, and J. Aaron. 2017. Case Study: Oso, Washington, landslide of March 22, 2014 - Material properties and failure mechanism. Journal of Geotechnical and Geoenvironmental Engineering, 143(5), 05017001. doi: 10.1061/(ASCE)GT.1943-5606.0001615

Steel, E. A., A. Marsha, A. H. Fullerton, J. D. Olden, N. K. Larkin, S. Lee, and A. Ferguson. 2019. Thermal landscapes in a changing climate: biological implications of water temperature patterns in an extreme year. Canadian Journal of Fisheries and Aquatic Sciences, 76(10), 1740-1756. doi: 10.1139/cjfas-2018-0244

Stevens-Rumann, C. S., Morgan, P. 2019. Tree regeneration following wildfires in the western US: a review. Fire Ecology, 15, 15. doi: 10.1186/s42408-019-0032-1

Stone, B., Hess, J. J., and Frumkin, H. 2010. Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? Environmental Health Perspectives, 118(10), 1425-1428. doi: 10.1289/ehp.0901879

Sun, N., H. Yan, M. S. Wigmosta, L. R. Leung, R. Skaggs, and Z. Hou. 2019. Regional snow parameters estimation for large-domain hydrological applications in the western United States. Journal of Geophysical Research: Atmospheres, 124(10), 5296-5313. doi: 10.1029/2018JD030140.

Sun, N., H. Yan, M. S. Wigmosta, J. Lundquist, S. Dickerson-Lange, and T. Zhou. 2022. Forest canopy density effects on snowpack across the climate gradients of the western United States mountain ranges. Water Resources Research 58(1), e2020WR029194. doi: 10.1029/2020WR029194.

Sun, N., Yan, H., Wigmosta, M.S. 2022. Datasets for characterizing extreme events relevant to hydrologic design over the conterminous United States. Scientific Data, 9, 154. doi: 10.1038/s41597-022-01221-9

Sun, N., Wigmosta, M., Zhou, T., Lundquist, J., Dickerson-Lange, S., Cristea, N. 2018. Evaluating the functionality and streamflow impacts of explicitly modelling forest–snow interactions and canopy gaps in a distributed hydrologic model. Hydrological Processes, 32, 2128-2140. doi: 10.1002/hyp.13150

Sun, N., Yearsley, J., Baptiste, M., Cao, Q., Lettenmaier, D. P., and Nijssen, B. 2016. A spatially distributed model for assessment of the effects of changing land use and climate on urban stream quality. Hydrological Processes, 30, 4779-4798. doi: 10.1002/hyp.10964

Suryan, R. M., Arimitsu, M. L., and Coletti, H. A. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific Reports, 11, 6235. doi: 10.1038/s41598-021-83818-5

Swain, D. L., D. Singh, D. Touma, and N. S. Diffenbaugh. 2020. attributing extreme events to climate change: a new frontier in a warming world. One Earth 2 (6), 522-527. doi: 10.1016/j.oneear.2020.05.011

Sweet, W. V., B. D. Hamlington, R. E. Kopp, C. P. Weaver, P. L. Barnard, D. Bekaert, W. Brooks, G. D. M. Craghan, T. Frederikse, G. Garner, A. S. Genz, J. P. Krasting, E. Larour, D. Marcy, J.J. Marra, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K. D. White, and C. Zuzak. 2022. Global and regional sea level rise scenarios for the United States: Up- dated mean projections and extreme water level probabilities along U.S. Coastlines, National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD.

Tan, Y., F. Zwiers, S. Yang, C. Li, and K. Deng. 2020. The role of circulation and its changes in present and future atmospheric rivers over western North America. Journal of Climate, 33(4), 1261-1281. doi: 10.1175/JCLI-D-19-0134.1

Tang, Q., Klein, S. A., Xie, S., Lin, W., Golaz, J.-C., Roesler, E. L., Taylor, M. A., Rasch, P. J., Bader, D. C., Berg, L. K., Caldwell, P., Giangrande, S., Neale, R., Qian, Y., Riihimaki, L. D., Zender, C. S., Zhang, Y., and Zheng, X. 2019. Regionally refined capability in e3sm atmosphere model version 1 (eamv1) and applications for high-resolution modelling. Geoscientific Model Development Discussion, 2019, 1-36.

Traynham, L., Palmer, R. and Polebitski, A. 2011. Impacts of future climate conditions and forecasted population growth on water supply systems in the Puget Sound Region. Journal of Water Resources Planning and Management, 137(4), 318-326.

Trenberth, K. E., J. T. Fasullo, and T. G. Shepherd. 2015. Attribution of climate extreme events. Nature Climate Change, 5(8), 725-730. doi: 10.1038/nclimate2657

United States (US). The Endangered Species Act as Amended by Public Law 97-304 (the Endangered Species Act Amendments of 1982). Washington: U.S. G.P.O., 1983.

United States Global Change Research Program (USGCRP). 2020. Coastal Integrated Hydro Terrestrial Modeling Workshop Report. https://climatemodeling.science.energy.gov/system/files/C-IHTM_Workshop_Report_Nov2020.pdf

Van Oldenborgh, G. J., M. F. Wehner, R. Vautard, F. E. L. Otto, S. Seneviratne, P. A. Stott, G. C. Hegerl, S. Y. Philip, S. F. Kew. 2022. Attributing and projecting heatwaves is hard: We can do better. Earth's Future, 10, e2021EF002271. doi: 10.1029/2021EF002271

Varhola, A., N. C. Coops, M. Weiler, and R. D. Moore. 2010. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. Journal of Hydrology, 392(3), 219-233. doi: https://doi.org/10.1016/j.jhydrol.2010.08.009

Waliser, D., Guan, B. 2017. Extreme winds and precipitation during landfall of atmospheric rivers. Nature Geosciences, 10, 179-183. doi: 10.1038/ngeo2894

Washington State Department of Health. 2021. Heat Wave of 2021. https://doh.wa.gov/emergencies/be-prepared-be-safe/severe-weather-and-natural-disasters/hot-weather-safety/heat-wave-2021

White, R., Anderson, S., Booth, J. 2022. The unprecedented Pacific Northwest heatwave of June 2021, Nature Portfolio, PREPRINT. doi: 10.21203/rs.3.rs-1520351/v1

Wilhere, G. F., Atha, J. B., Quinn, T., Tohver, I. and Helbrecht, L. 2017. Incorporating climate change into culvert design in Washington State, USA. Ecological Engineering, 104, 67-79. doi: 10.1016/j.ecoleng.2017.04.009

Wood, A. W., Leung, L. R., Sridhar, V. 2004. Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. Climatic Change, 62, 189-216.

Yabusaki, S. B., Myers-Pigg, A. N., Ward, N. D., Waichler, S. R., Sengupta, A., Hou, Z., Chen, X., Fang, Y., Duan, Z., Serkowski, J. A. and Indivero, J. 2020. Floodplain inundation and salinization from a recently restored first-order tidal stream. Water Resources Research, 56(7), e2019WR026850. doi: 10.1029/2019WR026850

Yan, H., Sun, N., Fullerton, A., and Baerwalde, M. 2021. Greater vulnerability of snowmelt-fed river thermal regimes to a warming climate. Environmental Research Letters, 16(5), 054006. doi: 10.1088/1748-9326/abf393

Yang, Z., G. Garcia-Medina, W. Wu, T. Wang, L. R. Leung, L. Castrucci, G. Mauger. 2019. Modeling analysis of the swell and wind-sea climate in the Salish Sea. Estuarine, Coastal and Shelf Science, 224, 289-300. doi: 10.1016/j.ecss.2019.04.043

Yang, Z., Wang, T., Branch, R., Xiao, Z., and Deb, M. 2021. Tidal stream energy resource characterization in the Salish Sea. Renewable Energy, 172, 188-208. doi: 10.1016/j.renene.2021.03.028

Yang, Z., Wang, T., Castrucci, L. and Miller, I., 2020. Modeling assessment of storm surge in the Salish Sea. Estuarine, Coastal and Shelf Science, 238, 106552. doi: 10.1016/j.ecss.2019.106552

Yang, Z., and Wang, T. 2015. Responses of estuarine circulation and salinity to the loss of intertidal flats - A modeling study. Continental Shelf Research, 111, 159-173. doi: 10.1016/j.csr.2015.08.011

Yang, Z., Wang, T., Voisin, N. and Copping, A., 2015. Estuarine response to river flow and sea-level rise under future climate change and human development. Estuarine, Coastal and Shelf Science, 156, 19-30.

Yang, Z., Wang, T., Khangaonkar, T. and Breithaupt, S., 2012. Integrated modeling of flood flows and tidal hydrodynamics over a coastal floodplain. Environmental Fluid Mechanics, 12(1), 63-80.

Yoon, J., Romero-Lankao, P., Yang, Y. C. E., Klassert, C., Urban, N., Kaiser, K. 2022. A typology for characterizing human action in multisector dynamics models. Earth's Future, 10, e2021EF002641. doi: 10.1029/2021EF002641

Young, S. R. 2012. Urban Heat Island (UHI) effect in the Puget Sound region: adaptation and biomimetic strategies to mitigate the effects of climate change. University of Washington ProQuest Dissertations Publishing, 1516056.

Zhang, Z., H. Song, P. L. Ma, V. E. Larson, M. Wang, X. Dong, and J. Wang. 2019. Subgrid variations of the cloud water and droplet number concentration over the tropical ocean: satellite observations and implications for warm rain simulations in climate models. Atmospheric Chemistry and Physics 19(2), 1077-1096. doi: 10.5194/acp-19-1077-2019

Zhong, S., Wang, T., Sciusco, P. 2021. Will land use land cover change drive atmospheric conditions to become more conducive to wildfires in the United States? International Journal of Climatology, 41, 3578-3597. doi: 10.1002/joc.7036

# Appendix A – Workshop Flyer

## Puget Sound Earth-Human System Dynamics Virtual Workshop

***Photo by Weston Norwood on Unsplash***

**Day 1: Monday March 7, 2022 9am-12pm PST**
**Day 2: Monday March 14, 2022 9am-12pm PDT**
**Day 3: Monday March 21, 2022 9am-12pm PDT**

Pacific Northwest National Laboratory (PNNL) is organizing a workshop on Puget Sound Earth-Human System Dynamics, to be held virtually on March 7, March 14 and March 21, 9 am - 12 pm Pacific Time.

Puget Sound is among highly vulnerable coastal regions affected by global warming with complex terrain ranging from mountains to coastal plains and diverse land cover from densely forested uplands to urbanized lowlands. Located in the northwest corner of Washington state, Puget Sound is characterized by complex terrain and strong urban to rural gradients in the maritime climate. With a diverse and evolving population, growing infrastructure and important ecological resources, it offers the opportunity to explore significantly contrasting geographic and hydroclimatic characteristics and human-Earth interactions, adding important perspectives to our understanding of the evolution and behavior of coastal regions in the United States. This region provides the unique opportunity for the Department of Energy (DOE) Office of Science Biological and Environmental Research Program (BER)'s Earth and Environmental Systems Modeling program (EESM) to advance and test their capabilities in advancing knowledge on multi-scale interactions at coastal interfaces. This study is supported by all three program areas in EESM—Earth System Model Development (ESMD), Regional and Global Modeling Analysis (RGMA), and MultiSector Dynamics (MSD)—bringing together modeling capabilities in understanding and simulating coastal systems and their vulnerability to climate change as well as other stresses including natural and human interactions.

The objectives of the workshop are to identify key knowledge gaps in modeling the interactions of natural and human systems in the region of the Puget Sound / Salish Sea, and to ascertain to what extent it might serve as a proxy for other mountainous maritime regions with strong urban to rural gradients. Specifically, we will identify future research activities that are aligned with DOE priorities and will inform research areas that could be part of DOE's long term, programmatic vision for improved understanding of Earth system science through modeling, data, and observation.

The workshop will bring together scientific experts to review the current state of knowledge; identify gaps in modeling capabilities, including gaps in measurements and data; and define research needs and key next steps to advance the frontiers of knowledge in regional hydroclimate, hydrologic extremes, and multisectoral dynamics in Puget Sound, as well as how these compare with needs in other regions. Workshop participants will include experts from universities, federal and state agencies, and key nongovernmental and private sector groups, including individuals that work with stakeholders and/or who bring experience and interest in co-production of knowledge and data to advance and expedite science-to-solutions.

**Workshop Structure and Process:**
The workshop will be held in three, 3-hour long virtual sessions, March 7, March 14 and March 21 from 9am to 12pm Pacific.
This workshop will be open to invited participants only and we expect about 50 participants.
Workshop co-chairs, the science committee and DOE have identified a set of key topics for the workshop to address.
We will focus on drivers, mechanisms and impacts of extreme events in the Puget Sound region, specifically heat wave and cold air outbreaks, extreme precipitation and floods, and droughts and wildfires. We will also look into drivers of Atmospheric-Terrestrial-Coastal-Human interactions at different scales, specifically climate variability and change and evolving human systems as drivers of interactions among water, energy and biogeochemical cycles and processes governing such interactions. We will follow with discussion of cross-cutting challenges and opportunities, and identification of research priorities aligned with DOE's mission and collaborative opportunities with other agencies.

**Outcome:** A report will be produced by September 2022 to DOE on our findings.
The report will summarize the discussions and findings of the literature review and workshops and make recommendations on future research activities that are aligned with DOE's interests and would enhance scientific understanding of key processes and interactions in the Puget Sound area as well as other regions.

**Background and motivation**: While Puget Sound has drawn considerable attention from a wide spectrum of stakeholders including scientists, resource managers, and policy makers, critical knowledge gaps remain with respect to the interactions between atmospheric processes, hydrological extremes, water management, and their interactions with energy and land systems in the highly complex coastal region. For example:

- Orographic precipitation is a key component of the water cycle of Puget Sound, dominating snowpack and streamflow variability. However, modeling orographic precipitation remains a challenge even on weather timescales.

- Under global warming, Earth System models project a robust increase in precipitation on the lee side of mountains and sharpening of storms, but the mechanisms driving these changes and the consequential hydrologic impacts are not well understood.
- Modeling and projecting snowpack and snow drought in maritime climates with complex terrain such as Puget Sound is also a major challenge, in part because snowpack variability exhibits greater sensitivity to uncertainties in atmospheric forcing and model structure compared to other snowy regions.
- Hydroclimatic drivers of wildfire and the subsequent impacts on regional ecosystems, human settlements, and air and water quality.
- Earth-Human system interactions are not well understood and their respective representation in sectoral models are most often missing the dynamic representation of drivers of change. This complexity leads to significant uncertainties in regional hydroclimatic and human systems dynamics under extreme conditions such as water scarcity or compound coastal flooding.

The research gaps briefly discussed above motivate a set of key research questions:

1. How do the complex terrain and coastal environment of Puget Sound interact with the large-scale environment and contribute to local-to-regional hydrologic extremes?
2. How well can regional and global models simulate the hydroclimate and integrated water cycle of the coupled human-earth system of Puget Sound?
3. How might climate variability and change and societal responses to climate change (e.g., energy, water management, and land use transitions) alter the water cycle in the Puget Sound and influence water availability, energy, food security, wildfires, and overall resilience both locally and remotely?
4. What insights can be gained by contrasting the climate impacts and societal response in Puget Sound with the mid-Atlantic, Arctic, Great Lakes and other coastal regions?

The workshop aims to engage the community in developing a deeper understanding of the current portfolio of research activities related to these overarching science questions, refine key research questions based on identified knowledge gaps, and identify strategic opportunities for DOE.

**Committee Chairs**

- Nathalie Voisin, PNNL
- Ning Sun, PNNL
- Debbie Rose, PNNL

**Scientific Committee Members**

- Bart Nijssen, UW
- Chris Nolte, EPA
- Guillaume Mauger, UW CIG
- Ian Kraucunas, PNNL
- Jeff Arnold, USACE
- Lynn McMurdie, UW
- Ruby Leung, PNNL
- Simone Alin, NOAA PMEL
- David Judi, PNNL

# Appendix B – Workshop Agenda

## Puget Sound Earth-Human System Dynamics
## Virtual Workshop Agenda

**Day 1 - Monday March 7 (9 am-12 pm PST)**

9:00 Welcome and introduction to scoping study and goals
9:10 Welcome from DOE and agency context
- Gary Geernaert, CESD division director, DOE BER
- Xujing Davis, ESMD program manager, DOE BER

9:20 Workshop agenda
9:30 Plenary presentations on extreme events (15-min each)
Flavio Lehner (Cornell) - Extreme Events Uncertainties and Attributions
Ruby Leung (PNNL) - Atmospheric Rivers
Ronda Strauch (Seattle City Light) - Powering through Extremes
10:15 Break
10:20 Breakout Sessions
Breakout #1: Heat wave and cold snaps
Breakout #2: Floods, Atmospheric Rivers and rain on snow
Breakout #3: Wildfires and droughts
11:35 Report outs
11:55 Next Steps and Adjourn

**Day 2 - Monday March 14 (9 am-12 pm PDT)**

9:00 Welcome and Context
9:05 Report back from Day 1 Breakouts
9:40 Plenary presentations: drivers of co-evolving Earth-Human systems (15-min each)
Nick Bond (University of Washington)
Marina Alberti (University of Washington)
10:10 Break
10:15 Breakout Sessions – Drivers of co-evolving Earth-Human systems
Breakout #1: Atmosphere/climate as drivers of co-evolving Earth-Human systems
Breakout #2: Hydroclimate drivers of co-evolving Earth-Human systems
Breakout #3: Human systems as drivers of co-evolving Earth-Human systems
11:40 Reconvene to summarize key scales and processes that emerged in breakout sessions
11:55 Next Steps and Adjourn

**Day 3 - Monday March 21 (9 am-12 pm PDT)**

9:00 Welcome and Summaries
9:10 Report back from Day 2 Breakouts, Q&A
10:00 DOE Program Areas
10:20 Modeling Challenges - Open Mic Discussion
11:45 Next steps and closing

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