PROJECTED SEA LEVEL RISE *for* WASHINGTON STATE

A 2018 ASSESSMENT

EARTH & SPACE SCIENCES
UNIVERSITY of WASHINGTON

CLIMATE IMPACTS GROUP
UNIVERSITY of WASHINGTON
College of the Environment

UNIVERSITY OF OREGON

Sea Grant Washington

USGS
science for a changing world

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The Washington Coastal Resilience Project (WCRP) is a three-year effort to rapidly increase the state's capacity to prepare for coastal hazards, such as flooding and erosion, that are related to sea level rise. The project will improve risk projections, provide better guidance for land use planners and strengthen capital investment programs for coastal restoration and infrastructure. Partners include:

Washington Sea Grant
Washington Department of Ecology
Island County
King County
NOAA Office of Coastal Management
Padilla Bay National Estuary Research Reserve
The City of Tacoma
The Nature Conservancy
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University of Oregon
University of Washington Climate Impacts Group
University of Washington Department of Earth and Space Sciences
University of Washington School of Marine and Environmental Affairs
Washington Department of Fish and Wildlife
Pacific Northwest National Laboratory

WASHINGTON **COASTAL RESILIENCE** PROJECT

The project is primarily funded by a grant from the NOAA Regional Coastal Resilience Grants Program (grant #NA16NOS4730015). Additional funds were provided by the State of Washington as well as the Pacific Northwest Climate Impacts Research Consortium (CIRC), which is partially funded by the Regional Integrated Sciences and Assessments program under NOAA grant #NA15OAR4310145.

Prepared for the Washington Coastal Resilience Project

July 2018 | University of Washington

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Acknowledgments

The authors thank Robert Kopp (Rutgers University), Robert Bindschadler (NASA), Li Erikson (USGS), Patrick Barnard (USGS), Lara Whitely Binder (King County) and Shaun O'Neil (King County) for their reviews and helpful contributions to this document. The primary source of funding for this work, and the Washington Coastal Resilience Project (WCRP) in general, was a NOAA Coastal Resilience grant from the NOAA Office of Coastal Management (grant #NA16NOS4730015). Additional funds were provided by the State of Washington as well as the Pacific Northwest Climate Impacts Research Consortium (CIRC), which is partially funded by the NOAA Regional Integrated Sciences and Assessments program (grant #NA15OAR4310145).

Recommended Citation

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 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. Prepared for the Washington Coastal Resilience Project. updated 07/2019

Technical Correction: Report citation was updated to include the University of Oregon, which was incorrectly attributed to Oregon State University in the 07/218 version.

Purpose of this Report

One of the objectives of the WCRP is to develop an updated assessment of projected sea level change for coastal Washington State and its relationship to coastal hazards such as flooding and erosion. Washington State has two previous assessments of sea level rise; one published in 2012 by the National Academies of Science (NRC, 2012), and another in 2008 (Mote et al., 2008). This report provides an updated set of sea level rise projections that incorporates the latest science, provides community-scale projections, and is designed for direct application to risk management and planning. Subsequent reports will describe new findings related to storm surge, waves, and efforts to integrate sea level rise in coastal planning and management.

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EXECUTIVE SUMMARY

Washington's coastal areas and marine waters are not only an important economic engine for the state but also provide an important sense of place and figure irreplaceably in the traditions and cultures of tribal communities. The state's coastlines also provide valuable ecosystem services that support human and natural communities alike. Sea level rise will exacerbate existing risks and vulnerabilities, such as shoreline and coastal bluff erosion, storm surge, flooding, and groundwater intrusion. This assessment provides new up-to-date projections for use in coastal habitat restoration, community and land-use planning, and infrastructure design and operations.

Washington State is due for a new assessment of sea level rise. The science has advanced significantly since the last assessment (NRC, 2012), in particular suggesting the potential for higher rates of sea level rise this century. In addition, previous assessments did not adequately account for differences in the rate of vertical land movement across the state, which affects how sea level rise is experienced on land. Finally, past studies have typically provided a low, middle, and high projection, with little guidance on how to interpret these in the context of sea level rise planning. We have developed a new set of projections that address each of these issues. Specifically, there are three distinguishing features of the new projections:

(1) **New Science.** Our projections are primarily drawn from a recent comprehensive assessment of global and regional sea level rise (Kopp et al., 2014). The new projections incorporate recent research indicating the potential for higher sea level rise in the 21st century.

(2) **Community-scale.** Projections are developed for 171 locations distributed along Washington's coastline. These account for variations in the rate of vertical land movement across the state.

(3) **Probabilistic.** We assess the likelihood, for a given greenhouse gas scenario, that sea level rise will reach or exceed a certain level relative to the present. This probabilistic approach may be better suited for application to risk management and planning.

Our study begins with a new set of projections for **absolute sea level rise** (the height of the ocean surface relative to a fixed, unmoving reference point, such as the center of the earth). However, the impacts of sea level rise will be felt via a change in height of the ocean surface relative to land. To estimate relative sea level rise, we combine separate estimates of absolute sea level rise and vertical land movement (uplift or subsidence), bringing them together to create the **relative sea level rise projections** described below.

Whereas we produce a single set of absolute sea level rise projections for the entire state of Washington (**Table 1**), there are important differences in vertical land movement along the state's coastlines. As a result, we produce local estimates of vertical land motion for 171 locations along Washington's coastline (**Figure 1**). Our relative sea level rise projections reflect these distributed estimates of vertical land motion, showing higher sea level rise in some places than in others. Although the rate of vertical land movement is generally small compared to absolute sea level rise projections – especially later in the 21st century – it can have a noticeable impact on observed and projected sea level in some locations.

TABLE 1: Absolute sea level rise projections, in feet, for Washington State. Projections are expressed in terms of the "probability of exceedance" for three different time periods (2050, 2100, and 2150) and two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period from 1991-2009. Projections for 2050 and 2100 the High greenhouse gas scenario (RCP 8.5, highlighted below) are also shown in **Figure 2. Examples of *location-specific* relative sea level rise projections are available in Table 2.**

PROJECTED ABSOLUTE SEA LEVEL CHANGE
(feet, averaged over each 19-year time period)

Time Period	Greenhouse Gas Scenario	Central Estimate (50%)	Likely[5] Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
				10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
2050 (2040-2059)	Low	0.6	0.4 - 0.8	0.9	1.2	1.8
	High	0.7	0.5 - 0.9	1.0	1.3	2.0
2100 (2090-2109)	Low	1.6	1.0 – 2.2	2.5	4.1	7.2
	High	2.0	1.4 - 2.8	3.1	4.8	8.3
2150 (2140-2159)	Low	2.5	1.5 - 3.8	4.4	8.5	16.2
	High	3.4	2.3 - 4.9	5.6	10.0	18.3

Future sea level depends on how much and how quickly atmospheric greenhouse gases cause the earth system to warm, as well as how sensitive each process contributing to sea level rise is to that warming. As a result, we develop a separate set of projections for two greenhouse gas scenarios, which can be thought of as representing "low" and "high" trajectories of future greenhouse gas emissions.

The projections are probabilistic. For each greenhouse gas scenario, a set of probabilities describe the likelihood that sea level rise will meet or exceed a particular amount (i.e.: our likelihoods refer to the "probability of exceedance" of a given amount of sea level rise). Even for a single greenhouse gas scenario, there is often a wide range among projections; this primarily reflects the uncertainty in the observed and modeled response of sea level rise to climate change. The primary contributor to this range is the large uncertainty in the rate and magnitude of ice melt from Antarctica and, to a somewhat lesser extent, Greenland. The likelihoods allow users to select probabilities to align with a particular decision context or risk management approach.

As an example, our absolute sea level rise projections suggest a central estimate – corresponding to a 50% chance that absolute sea level will rise by at least that amount – of 1.6 ft for a low greenhouse gas scenario and 2.0 feet for a high greenhouse gas scenario, by 2100.[1] At the low end, the projections give an 83% probability that sea level will rise by at least 1.0 or 1.4 feet, again for a low and a high greenhouse gas scenario, respectively. At the high end, the projections suggest a rapid acceleration in the rate of sea level rise over the 21st century: the projections give a 1% probability, for example, that absolute sea level rise will reach or exceed 4.1 feet for a low greenhouse gas scenario, and 4.8 feet for a high greenhouse gas scenario, by 2100.

Recent research has led to an increase in the high-end projections for sea level rise, and it is possible that future research could do the same (e.g., Kopp et al., 2014). Given the difficulties that this would cause for planners, we have also provided an extreme high-end projection, which we consider to represent an approximate physical upper limit for sea level rise. In our probabilistic framework we derive this from the 0.1% probability of exceedance for the high greenhouse gas scenario, which we find is consistent with other assessments of the maximum possible change in sea level by the end of the 21st century. We project an upper limit of 8.3 feet of absolute sea level rise by 2100.

1. All projections are given relative to the average sea level for 1991-2009.

Our results differ from past projections. Comparing the projections for 2100, our central estimate (1.6-2.0 ft) is lower than the central estimate from the last regional report on sea level rise (2.3 ft; NRC, 2012). Previous studies did not include an estimate of likelihoods, but the high end from the NRC - (2012) report (4.5 ft) is much lower than in the new projections (7.2-8.3 ft), and instead corresponds to about the 1% probability of exceedance in our current study (4.1-4.8 ft). A more in-depth review of the science, including comparisons with previous work, can be found in **Appendix B**.

Image credit: Hoh River mouth by Sam Beebe, used under CC BY 2.0

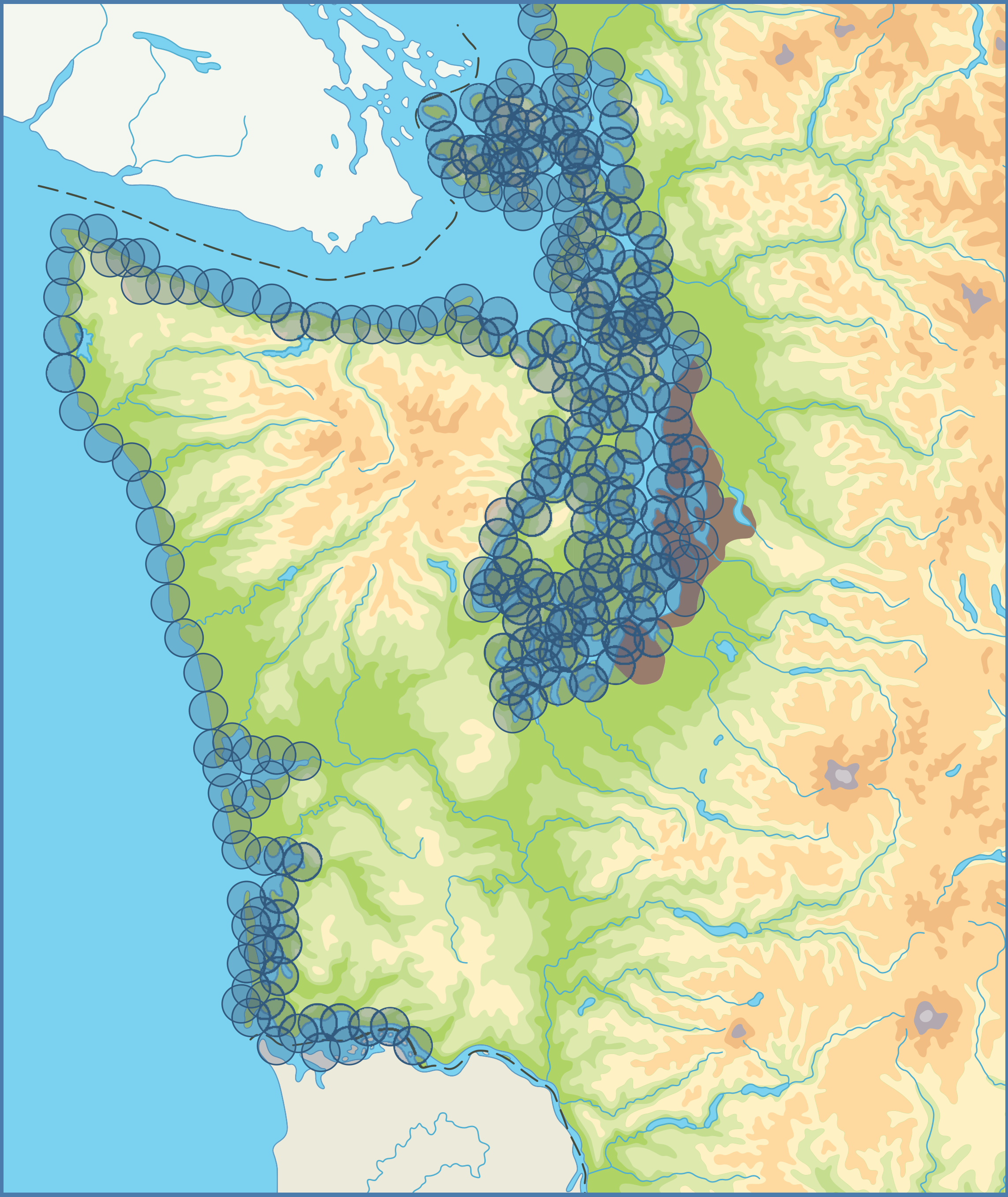
The projections cited above refer to absolute sea level rise, and do not account for vertical movement of the land surface. Our relative sea level rise projections track with these absolute sea level rise projections but are modulated by the local rates of vertical land motion. For example, on the northwest Olympic Peninsula near Neah Bay, where the land is uplifting rapidly, the relative sea level rise projections are lower than the absolute sea level rise projections. In areas where the land is subsiding, such as central Puget Sound, the relative sea level rise projections are slightly higher than the absolute sea level rise projections. We provide relative sea level rise projections for 171 individual locations along the Washington coastline that account for these local changes under the two greenhouse gas scenarios. Projections for each location can be downloaded from the project website: www.wacoastalnetwork.com/wcrp-documents.html

Although we assume that our assessed rates of vertical land motion remain constant over time, a large Cascadia earthquake could suddenly reverse the estimated trend in some parts of Washington State. Although not incorporated quantitatively in our relative sea level rise projections, we provide information about the potential change in land elevation associated with such an event.

Finally, it is worth emphasizing that sea level rise projections are different from Federal Emergency Management Agency (FEMA) flood insurance studies, because (1) FEMA studies only consider past events , and (2) flood insurance studies only consider the 100-year event, whereas sea level rise affects coastal water elevations at all times.

Our new projections reflect the latest science on sea level rise and are an improvement over previous assessments (**see Appendix B**). Over time, these will undoubtedly be updated as new science becomes available. Until that time, we recommend using these new projections for coastal impacts assessments within the state of Washington.

FIGURE 1: Map showing the 171 locations along Washington's coastline for which relative sea level projections are provided. At each location, a different estimate of vertical land movement and associated uncertainty is combined with the statewide projections for absolute sea level to produce a locally-specific set of projections for relative sea level rise. Projections for each location can be downloaded from the project website: www.wacoastalnetwork.com/wcrp-documents.html.



INTRODUCTION

This report provides a summary of new projections of sea level rise for Washington State. These projections improve on previous estimates (NRC, 2012 ;, Mote et al., 2008) by:

- Incorporating new science about the processes contributing to global sea level rise, including new understanding of the dynamics of melt for the Greenland and Antarctic ice sheets,
- Accounting for community-scale differences in vertical land movement along Washington's coastlines, and
- Estimating the probabilities that various amounts of sea level rise will occur for a given greenhouse gas scenario.

These projections can be used to inform coastal risk assessments, planning, decision making and ongoing management for Washington's coastal communities.

Future greenhouse gas emissions depend on human behavior: technological innovation, geopolitics, population growth, etc. As a result, there is no reliable way to estimate the probability of following a particular emissions trajectory. Instead, we have developed a separate set of probabilistic projections for both a low and a high greenhouse gas scenario.[2]

We present our projections in terms of the probability of exceedance, or the likelihood that sea level rise will meet or exceed a particular elevation relative to contemporary sea level. Recent research has emphasized the potential for large amounts of sea level rise, and today's high-end projections are much higher than those of previous studies. In order to minimize the chance that our high-end projections are similarly revised upward in the future, we have also included a very high magnitude projection, which multiple studies indicate is a likely upper bound for future sea level rise by 2100 (**Appendix B**).

The probabilities associated with our projections are fundamentally different from the probability associated with a coastal flood event, for example, a 100-year flood. The 100-year flood – defined as the level of flooding having a 1%

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2. For more on greenhouse gas scenarios, see Section 1 of Mauger et al., 2015. Note two other greenhouse gas scenarios are omitted: RCP 2.6 and RCP 6.0. Recent research suggests that it is no longer feasible to achieve the dramatic reductions required under RCP 2.6 (e.g., Davis and Socolow, 2014; Pfeiffer et al., 2016). RCP 6.0 is not included because of a limited amount of projections that continue past 2100.

Image credit: King Tide Nov 29, 2014 Southworth by Fletcher Sandbeck, used under CC BY 2.0

chance of occurring in any given year – is derived from historical observations, and is calculated based on the frequency with which past high-water events, or the meteorological drivers of those events (e.g., high winds), have occurred. Our sea level rise projections, in contrast, are derived using models to project changes over time into the future. As a result, our sea level rise projections incorporate uncertainties in models as well as in the observations used to adjust and refine those models.[3]

Finally, we emphasize that sea level rise projections are different from the coastal flood risk assessments performed in a typical Federal Emergency Management Agency (FEMA) study. Specifically: (1) The current study concerns future changes in sea level, whereas FEMA flood maps are based on historical observations and assume no long-term change in risk, and (2) FEMA studies are focused on one specific event – the 100-year coastal flood – and do not address water levels during normal tides or other storm intensities. Our projections, in contrast, concern the long-term change in sea level, affecting the height of the water surface at all tidal elevations as well as during storm events.

This report begins by introducing our projections of absolute sea level change (the height of the ocean surface relative to a fixed, unmoving reference point, such as the center of the earth). Because sea level rise will be experienced as a change in the height of the ocean surface relative to land, we then estimate relative sea level change, which combines separate estimates of absolute sea level rise and vertical land movement (uplift or subsidence).

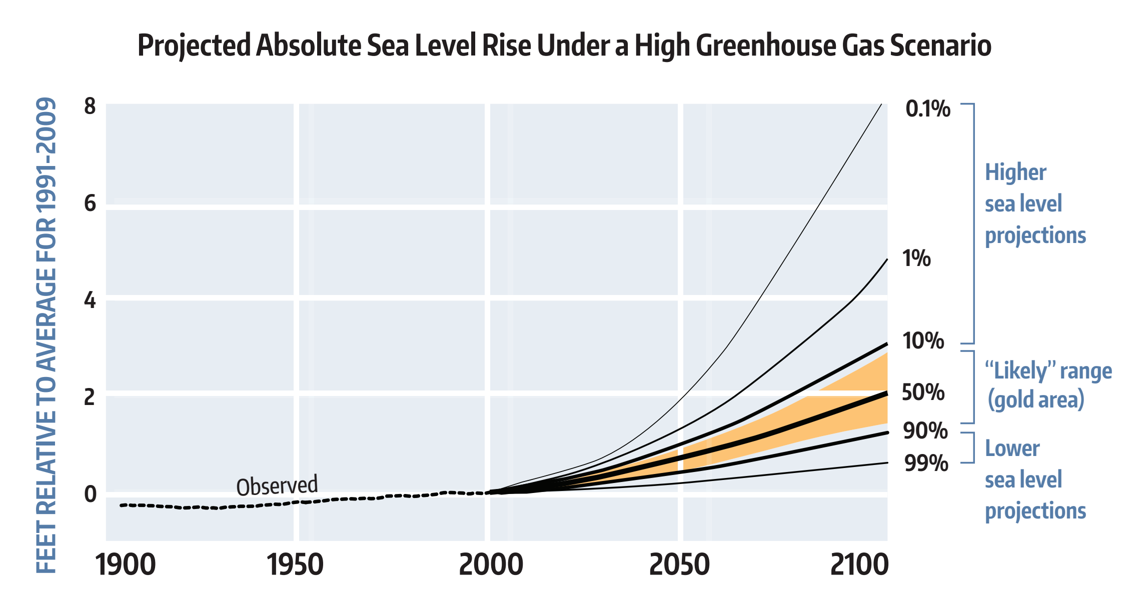
3. In statistical terms, this is the distinction between "Frequentist" vs. "Bayesian" approaches. We adopt a Bayesian approach to projecting future sea level after Kopp et al. (2014).

ABSOLUTE SEA LEVEL PROJECTIONS

Overview

This section describes our new projections of absolute sea level rise for Washington State (**Figure 2**). Absolute sea level refers to the height of the ocean surface, irrespective of any movement of the land. Changes in absolute sea level are evaluated relative to a "geocentric" reference frame – i.e., relative to the center of the earth – as opposed to the elevation of the land surface. Absolute sea level change can be combined with estimates of vertical land movement (e.g., uplift and subsidence) to project changes in "relative" sea level. Relative sea level rise is more applicable to community planning, since ultimately it is the relative change in sea level that will determine impacts on land.[4]

FIGURE 2: Absolute sea level rise projections, through 2100, for a high greenhouse gas scenario (RCP 8.5), for Washington State. Projections are based on Kopp et al. (2014) and observed variations in absolute sea level are shown for 1907-2007.[4] All results are shown relative to the average for 1991-2009. The probability values are "probabilities of exceedance", i.e., the current best assessment of the likelihood that absolute sea level will rise by at least a given change in elevation.



4. The observed absolute sea level change estimates in **Figure 2** were obtained by removing our estimate of vertical land movement (**Appendix C**) from the observed relative sea level trends, averaged over seven Washington State tide gauges. The resulting time series of monthly absolute sea level was then smoothed with a 19-year moving average.

Although there is potential for different rates of absolute sea level rise across Washington's coast, these differences are very small (generally less than 0.3 feet, about 4 inches, by the end of the century; **Appendix A**) and are not well resolved by current modeling. As a result, we produced a single set of absolute sea level rise projections for all of Washington State.

Our projections describe potential changes in long-term average absolute sea level (i.e., over multiple years or decades), relative to 1991-2009. Short-term water level variability – e.g., due to storms, El Niño, and other processes – can temporarily add to or reduce the rate of sea level change, and will continue to do so into the future.

The new projections are probabilistic, in that they describe the full range of possible future sea level changes for a given greenhouse gas scenario, with associated probabilities of exceedance within that range. Probabilities were determined based on the current science concerning each individual component of sea level rise (Kopp et al., 2014, see discussion below). This new approach is different from previous assessments for Washington State (Mote et al., 2008; NRC, 2012), which presented future ranges, but without a comprehensive assignment of likelihood.

SEA LEVEL AND DATUMS

Sea level typically refers to the long-term (i.e., over multiple years or decades) average sea surface height relative to land (often described as "Mean Sea Level", or MSL). In our study, projections are intentionally averaged over a 19-year period, since this encompasses the 18.6-year lunar cycle in tidal range. At any given time, the actual sea level could be lower or higher than this average due to tides, storms, or changes in wind and ocean currents. These short-term variations will continue into the future, and may be important to consider in planning. In the current study we average over these short-term influences on sea level in order to emphasize the long-term rise in sea level due to climate change.

Tide gauge observations are always reported relative to some common baseline, or "datum". This is a critical detail in coastal project planning and design, since the use of an incorrect datum can lead to an erroneous assessment of risk. Our results, however, are not tied to any particular datum. This is because we assess the ***change*** in absolute and relative sea level over time, which could be applied to any water surface elevation.

It is possible that tidal ranges may be influenced by sea level rise, as has been demonstrated for other locations around the globe at relatively high sea level rise magnitudes (e.g., Idier et al., 2017). However, this is very likely a minor effect, and it has not been quantified for the State of Washington. As a result, our projections assume that tidal ranges remain the same in the future.

Results

Our new absolute sea level rise projections are summarized in **Table 1** and **Figure 2**; the complete set of projections can be found in Appendix A. Whereas **Figure 2** shows results for just one greenhouse gas scenario (the high RCP 8.5 scenario), **Table 1** summarizes the absolute sea level rise projections for both a low and a high greenhouse gas scenario. In both, projections are averaged over the 19-year period indicated in the table, are shown in feet relative to contemporary sea level for Washington State, and are evaluated for a range of probabilities of exceedance.

By 2100, projections for all scenarios indicate a high likelihood (~50% probability or greater) of at least 1.5 feet of sea level rise, with the potential for more than 8 feet at the upper end of the distribution. At the low end, there is an 83% probability that sea level will rise by at least one foot by 2100, for a low greenhouse gas scenario (RCP 4.5).

TABLE 1: Absolute sea level rise projections, in feet, for Washington State. Projections are expressed in terms of the "probability of exceedance" for three different time periods (2050, 2100, and 2150) and two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Projections for 2050 and 2100 for RCP 8.5 (highlighted below) are also shown in **Figure 2. Examples of *location-specific* relative sea level rise projections are available in Table 2.**

PROJECTED ABSOLUTE SEA LEVEL CHANGE
(feet, averaged over each 19-year time period)

Time Period	Greenhouse Gas Scenario	Central Estimate (50%)	Likely[5] Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
				10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
2050 (2040-2059)	Low	0.6	0.4 - 0.8	0.9	1.2	1.8
	High	0.7	0.5 - 0.9	1.0	1.3	2.0
2100 (2090-2109)	Low	1.6	1.0 – 2.2	2.5	4.1	7.2
	High	2.0	1.4 - 2.8	3.1	4.8	8.3
2150 (2140-2159)	Low	2.5	1.5 - 3.8	4.4	8.5	16.2
	High	3.4	2.3 - 4.9	5.6	10.0	18.3

The projected rise in sea level for 2050 is essentially the same for all greenhouse gas scenarios, since both scenarios show a similar amount of warming by that time. In contrast, future emissions make a big difference in the amount of sea level rise projected for 2100 and 2150. By 2100, for example, the median projection (50% probability of exceedance) is nearly a half foot lower for the low greenhouse gas scenario than it is for the high greenhouse gas scenario.

Our results differ from past projections. Comparing the projections for 2100, our central estimate (1.6-2.0 ft) is lower than the central estimate from the last regional report on sea level rise (2.3 ft; NRC, 2012). Previous studies did not include an estimate of likelihoods, but the high end from the last report (4.5 ft) is much lower than in the new projections (7.2-8.3 ft), and instead corresponds to about the 1% probability of exceedance in our current study (4.1-4.8 ft). A more in-depth review of the science, including comparisons with previous work, can be found in **Appendix B**.

Approach

This section briefly describes our approach to estimating future absolute sea level rise in Washington State; a broader literature review discusses the components of sea level rise in greater detail and can be found in **Appendix B**. Our approach makes use of tools and methods developed by Kopp et al. (2014), who estimate full probability distributions of each of the "climatically-controlled" components of sea level change, as follows:

- **Ocean Processes.** Warming waters cause sea level to rise ("thermal expansion"), while shifting winds and ocean currents can cause sea level to rise in some places and fall in others. In both cases, changes are assessed using global climate model projections from Phase 5 of the Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012).
- **Land-Based Glaciers and Ice Caps.** Melting land ice contributes to sea level rise. This category includes all land ice except the Greenland and

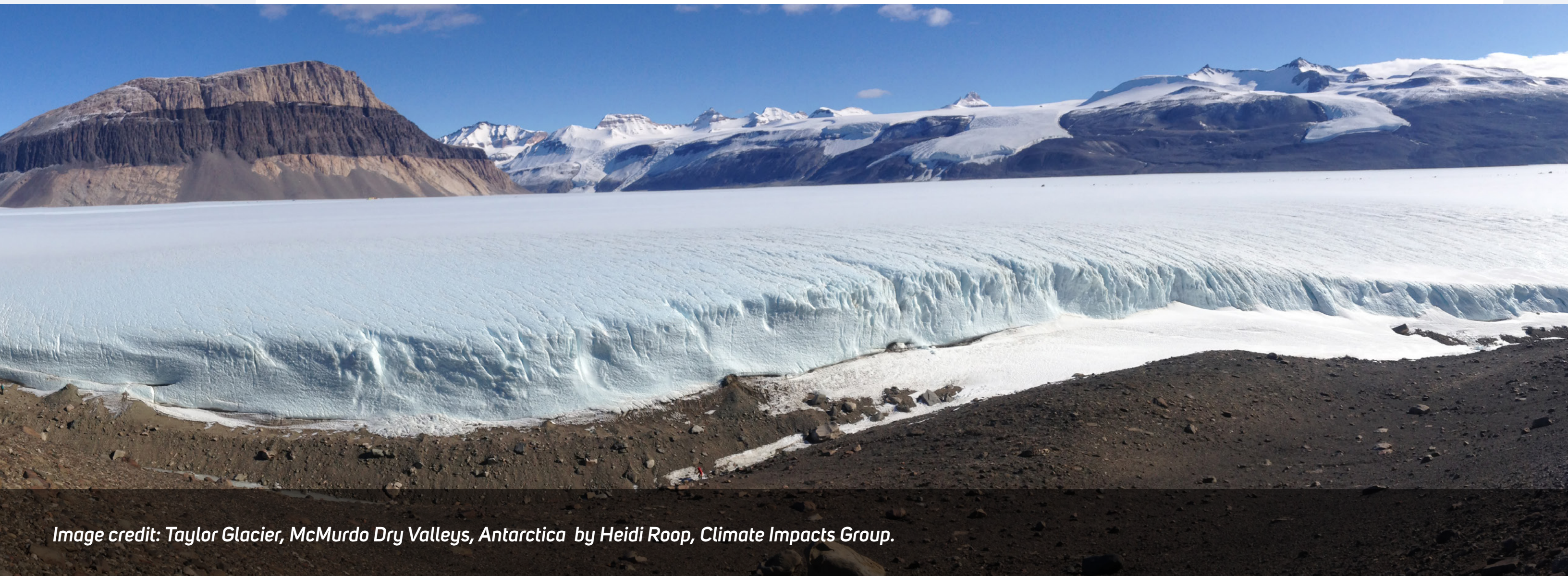


Image credit: Taylor Glacier, McMurdo Dry Valleys, Antarctica by Heidi Roop, Climate Impacts Group.

Antarctic ice sheets. Projections of land-based ice melt and its contribution to sea level rise are based on the model of Marzeion et al. (2012). As above, changes are assessed using climate projections from CMIP5.

- **Ice Sheets.** Changes in the size of the Greenland and Antarctic ice sheets also affect sea level. Ice sheets are treated separately from other land-based ice because the dynamics of ice movement are complex and are particularly important in Greenland and Antarctica. The median and likely[5] range among the projections of future ice sheet melt stem from the IPCC (2013) report, while the upper extremes are obtained from the expert elicitation results of Bamber and Aspinall (2013).

Other smaller contributors are also included in the Kopp et al. (2014) analysis. For example, they apply a model based on the approach of Mitrovica et al. (2011), to account for the change in gravitational pull of glaciers and ice sheets as they shrink in size. This is often referred to as "sea level fingerprinting", and can cause sea level to rise more rapidly in some places than others, and even cause sea level to fall in a few isolated areas very close to the ice sheets. There are also other factors that are not directly influenced by climate change, including retention of water behind man-made reservoirs (which lowers sea level), groundwater extraction (which raises sea level once the extracted water reaches the ocean), and even the ongoing response of the Earth's crust to the last ice age, a process known as "Glacial Isostatic Adjustment" (GIA). These processes are also accounted for in our projections.

We depart from the Kopp et al. (2014) approach in our estimates of the influence of GIA on absolute sea level rise. Because GIA concerns movement of the earth's crust and underlying mantle, it affects both vertical land motion and – via changes in the shape of ocean basins – absolute sea level. Kopp et al. (2014) developed a combined estimate that includes both consequences of GIA along with other influences on local relative sea level, such as plate tectonics. In our analysis, we develop separate estimates of the effects of GIA on vertical land movement and absolute sea level rise. This allows us to develop detailed, spatially varying estimates of vertical land movement along all of Washington's coastline, beyond simply the locations of high quality tide gauge records (**Appendix C**). Since our vertical land movement estimates do not include the influence of GIA on absolute sea level rise, these were obtained separately from **Appendix B** of NRC (2012, **Table B.2**).

5. We have adopted the IPCC terminology that relates likelihood statements to specific probabilities. In this case, "likely" refers to a confidence level of 66% or above. See www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Future sea level rise estimates are produced using a "Monte Carlo" approach, in which the probability distribution for each component of sea level rise (ocean processes, land-based glaciers and ice caps, ice sheets, sea level fingerprinting, GIA, etc.) is sampled randomly, then added together to develop one estimate of future sea level rise. This process is repeated 10,000 times, each time producing a new estimate of future sea level rise. The result is a probability distribution of sea level rise for a particular time period and scenario, from which we can estimate the amount of sea level rise associated with specific probabilities of exceedance. This approach is repeated for each decade (from 2000 to 2150) and for a low and a high greenhouse gas scenario (Kopp et al., 2014).

For the purpose of this assessment we chose the 99% and 1% probability of exceedance levels as the bounds of possible future sea level rise. However, processes that could lead to extreme high-end sea level rise are currently an area of intense scientific and planning interest. In particular, recent modeling of the Antarctic Ice Sheet suggests that the best estimate for 21st century sea level rise may be higher than previously estimated (DeConto and Pollard, 2016). Although this study highlights important mechanisms that may lead to accelerated Antarctic melt, the authors note that their results are preliminary and "should not be viewed as actual predictions." Nonetheless, it is possible that future research could shift future projections upward. As a result, we have also included an upper limit or very high magnitude sea level rise projection, associated with an extremely low probability of exceedance (0.1%). The inclusion of this low probability, high impact sea level rise projection is in keeping with recent sea level rise planning work in other regions (e.g., Griggs et al., 2017; Sweet et al., 2017; Kopp, personal communication). This high-end projection is discussed in more detail in **Appendix B**.

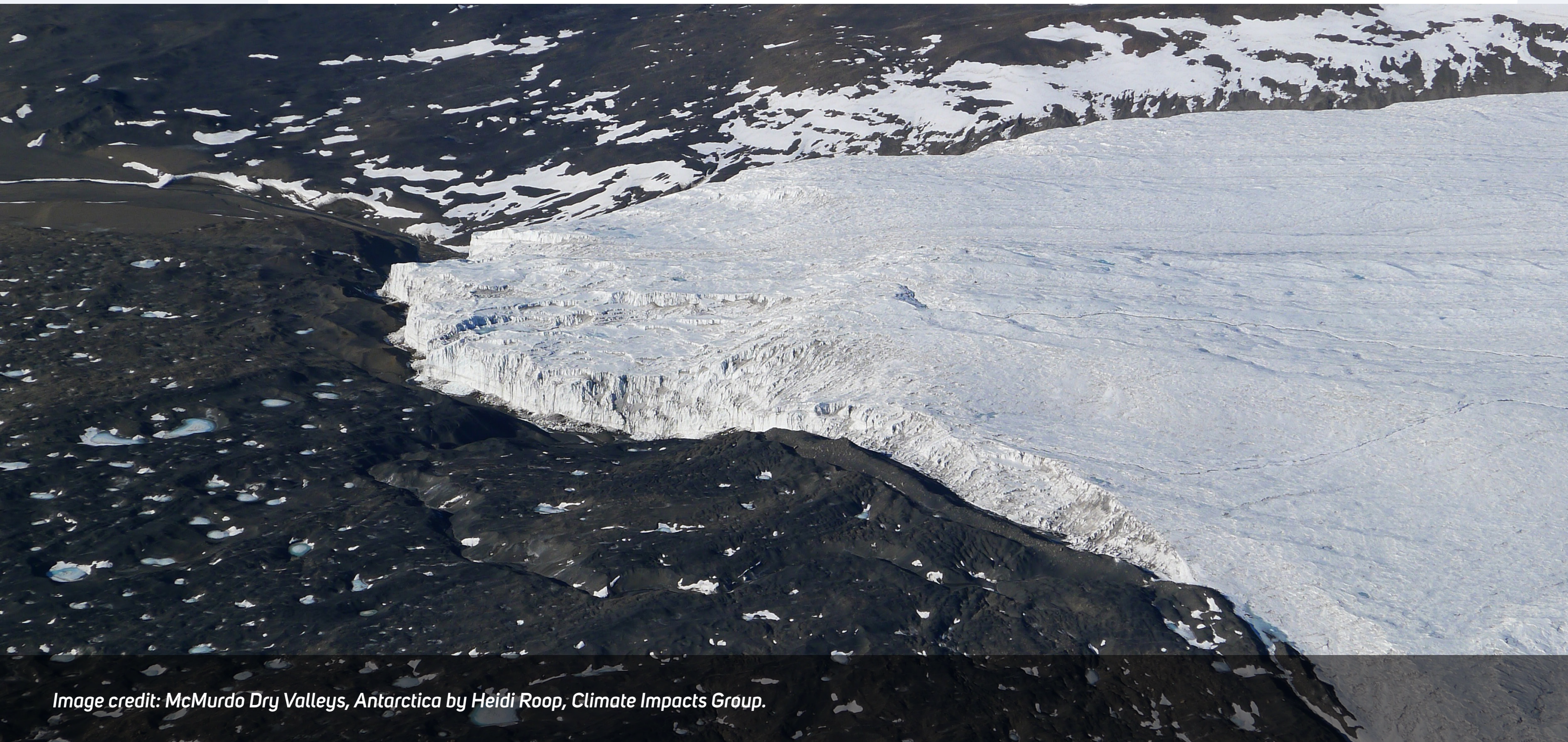


Image credit: McMurdo Dry Valleys, Antarctica by Heidi Roop, Climate Impacts Group.

RELATIVE SEA LEVEL PROJECTIONS

Overview

Relative sea level is the long-term (over multiple years or decades) average sea surface height relative to a fixed point on land. Relative sea level changes reflect both changes in absolute sea level and vertical movement of the land surface (i.e., subsidence or uplift). In Washington State, vertical land movement can have a non-negligible impact on near-term changes in observed and projected relative sea level rise (Mazotti et al., 2008).

As with the absolute sea level rise projections, our relative sea level rise projections (**Table 2**) describe potential changes in long-term average sea level (i.e., over

TABLE 2: Relative sea level projections, in feet, for three of the 171 locations along Washington's coastline. Example locations in Washington include the Taholah, Neah Bay, and Long Beach. Projections are expressed in terms of the "probability of exceedance" for 2100 (2090-2109) under two different greenhouse gas scenarios (RCP 4.5 ["Low"] and RCP 8.5 ["High"]; van Vuuren et al., 2011). Projected changes are assessed relative to contemporary sea level, which we define as the average sea level over the 19-year period 1991-2009. Data for all 171 locations are available at www.wacoastalnetwork.com/wcrp-documents.html.

PROJECTED RELATIVE SEA LEVEL CHANGE FOR 2100
(feet, averaged over a 19-year time period)

Location	Vertical Land Movement Estimate	Greenhouse Gas Scenario	Central Estimate (50%)	Likely Range (83-17%)	Higher magnitude, but lower likelihood possibilities		
					10% probability of exceedance	1% probability of exceedance	0.1% probability of exceedance
Tacoma (47.3N, 122.4W)	-0.5 ± 0.2	Low	2.1	1.5-2.7	3	4.6	7.9
		High	2.5	1.9-3.3	3.6	5.3	8.8
Neah Bay (48.4N, 124.6W)	1.1 ± 0.3	Low	0.5	-0.1 - 1.2	1.5	3.1	6.3
		High	1	0.3 - 1.7	2	3.8	7.4
Taholah (47.4N, 124.3W)	0.3 ± 0.5	Low	1.3	0.6-2.1	2.4	3.9	7.1
		High	1.7	1.0-2.6	2.9	4.6	8.1

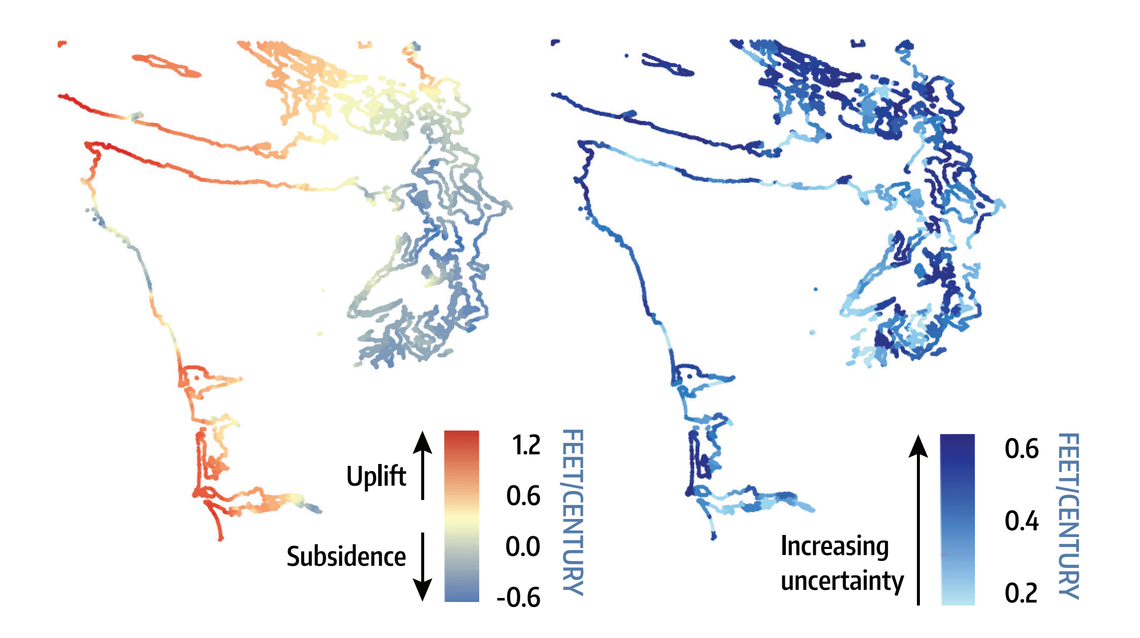
multiple years or decades), relative to 1991-2009. Our projections are probabilistic: for each greenhouse gas scenario, the range among projections is expressed as the probability that sea level rise will reach or exceed a particular change in elevation (this is often referred to as the "probability of exceedance").

Results

Coastal vertical land movement varies in Washington State (**Figure 3**), which translates into variations in relative sea level. Our vertical land movement estimates were produced on a 0.1-degree grid (equivalent to roughly 5-7 miles). The same resolution is used for our relative sea level rise projections. The projections are summarized in a series of excel files, produced for each of the 171 coastal locations that correspond to the 0.1-degree grid, each with a separate worksheet for each greenhouse gas scenario ("Low": RCP 4.5 and "High": RCP 8.0; **Figure 4**). All projections can be found on the WCRP project website: www.wacoastalnetwork.com/wcrp-documents.html.

By construction, the relative sea level rise projections reflect variations in the estimated rate of vertical land movement along Washington's coastline (e.g. **Table 2**). Areas that are estimated to be uplifting rapidly (e.g., the northwest tip of the Olympic Peninsula) have lower projected changes in relative sea level

FIGURE 3: Vertical land movement best estimate rates (left) expressed in rates of feet/century, and their uncertainties (1 standard deviation, right) as estimated for Washington's coastline.



when compared to areas (e.g., parts of central Puget Sound) that are estimated to be subsiding (**Table 2 and Figure 3**). The uncertainty in coastal vertical land movement estimates can also be seen in the relative sea level rise projections. For example, the large uncertainty in vertical land movement for the Long Beach peninsula leads to a larger difference between the 17 and 83% probability of exceedance projections than in adjacent areas.

A key assumption in our analysis is that our assessed rates of vertical land motion will continue, uninterrupted, through 2150. Seismic activity can cause sudden changes in land elevation, thus altering sea level. Although earthquakes are difficult to predict, modeling suggests that a large earthquake, occurring along the Cascadia subduction zone fault, could result in a sudden change in land elevation along large swaths of Washington's coast. This "co-seismic" land level change on the coast is not built into our relative sea level rise projections. Given its potential importance for planning, we obtained model estimates of land level changes for an earthquake with a return frequency of 500 years.[6] This information is included in our relative sea level rise tables for Washington's coast (**Figure 4**, see **Appendix C** for a more in-depth discussion).

Smaller earthquakes, such as on the Seattle fault, can also cause sudden changes in land elevation. However, these changes occur over a much smaller area. It is beyond the scope of this assessment to estimate these smaller potential changes for all of coastal Washington. Communities that are adjacent to crustal faults[7] may choose to undertake a more detailed and localized analysis to take into account possible relative sea level changes associated with local faults.

Approach

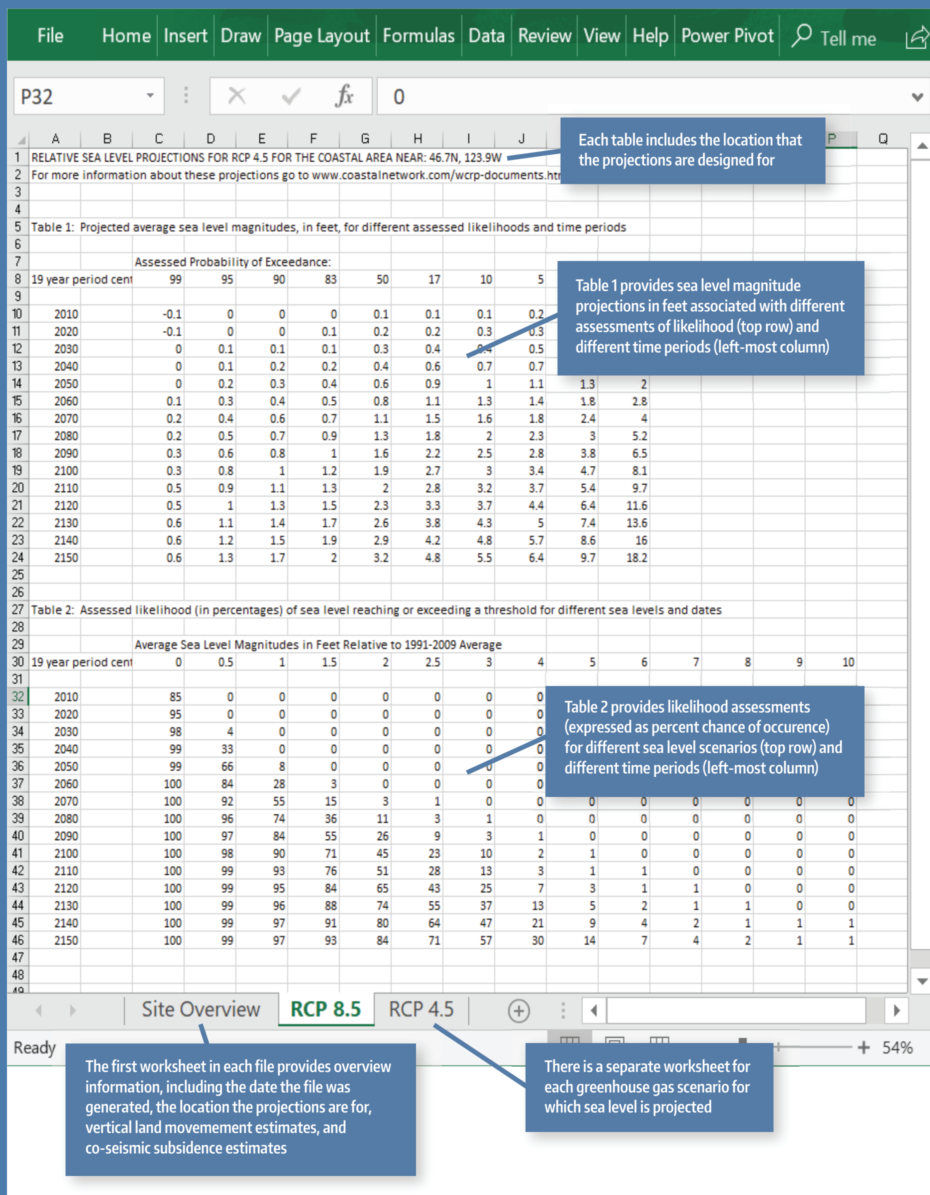
We developed relative sea level rise projections by incorporating our assessment of absolute sea level change, and its uncertainty, with our estimated rates of coastal vertical land movement and their uncertainties. As noted in the previous section, variations in absolute sea level across Washington State are small and are not well characterized by current modeling. As a result, we produce a single set of absolute sea level rise projections for all of Washington State. In contrast, our vertical land movement estimates are spatially distributed, with notable variations along the state's coastline (**Figure 3**).

6. The geologic record indicates that there have been seven large subduction zone earthquakes in the Cascadia subduction zone over the last 3500 years, yielding a return interval of 500 years.

7. See https://geologyportal.dnr.wa.gov/#natural_hazards

Previous investigations have estimated the rate of vertical land movement for Washington State (Mote et al., 2008; NRC, 2012). However, there are a number of limitations to these previous assessments – in particular, previous studies either assumed the same rate for the entire state, or limited their assessment to a very small number of locations along the coastline. As a result, we opted to conduct our own vertical land movement assessment that made use of over 500

FIGURE 4: Example relative sea level table, with descriptions showing how the data are organized.



RELATIVE SEA LEVEL PROJECTIONS FOR RCP 4.5 FOR THE COASTAL AREA NEAR: 46.7N, 123.9W

For more information about these projections go to www.coastalnetwork.com/wcrp-documents.htr

Table 1: Projected average sea level magnitudes, in feet, for different assessed likelihoods and time periods

	Assessed Probability of Exceedance:									
19 year period cent	99	95	90	83	50	17	10	5	[illegible]	[illegible]
2010	-0.1	0	0	0	0.1	0.1	0.1	0.2	[illegible]	[illegible]
2020	-0.1	0	0	0.1	0.2	0.2	0.3	0.3	[illegible]	[illegible]
2030	0	0.1	0.1	0.1	0.3	0.4	0.4	0.5	[illegible]	[illegible]
2040	0	0.1	0.2	0.2	0.4	0.6	0.7	0.7	[illegible]	[illegible]
2050	0	0.2	0.3	0.4	0.6	0.9	1	1.1	1.3	2
2060	0.1	0.3	0.4	0.5	0.8	1.1	1.3	1.4	1.8	2.8
2070	0.2	0.4	0.6	0.7	1.1	1.5	1.6	1.8	2.4	4
2080	0.2	0.5	0.7	0.9	1.3	1.8	2	2.3	3	5.2
2090	0.3	0.6	0.8	1	1.6	2.2	2.5	2.8	3.8	6.5
2100	0.3	0.8	1	1.2	1.9	2.7	3	3.4	4.7	8.1
2110	0.5	0.9	1.1	1.3	2	2.8	3.2	3.7	5.4	9.7
2120	0.5	1	1.3	1.5	2.3	3.3	3.7	4.4	6.4	11.6
2130	0.6	1.1	1.4	1.7	2.6	3.8	4.3	5	7.4	13.6
2140	0.6	1.2	1.5	1.9	2.9	4.2	4.8	5.7	8.6	16
2150	0.6	1.3	1.7	2	3.2	4.8	5.5	6.4	9.7	18.2

Table 2: Assessed likelihood (in percentages) of sea level reaching or exceeding a threshold for different sea levels and dates

	Average Sea Level Magnitudes in Feet Relative to 1991-2009 Average													
19 year period cent	0	0.5	1	1.5	2	2.5	3	4	5	6	7	8	9	10
2010	85	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2020	95	0	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2030	98	4	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2040	99	33	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2050	99	66	8	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2060	100	84	28	3	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2070	100	92	55	15	3	1	0	0	0	0	0	0	0	0
2080	100	96	74	36	11	3	1	0	0	0	0	0	0	0
2090	100	97	84	55	26	9	3	1	0	0	0	0	0	0
2100	100	98	90	71	45	23	10	2	1	0	0	0	0	0
2110	100	99	93	76	51	28	13	3	1	1	0	0	0	0
2120	100	99	95	84	65	43	25	7	3	1	1	0	0	0
2130	100	99	96	88	74	55	37	13	5	2	1	1	0	0
2140	100	99	97	91	80	64	47	21	9	4	2	1	1	1
2150	100	99	97	93	84	71	57	30	14	7	4	2	1	1

individual vertical land movement observations along Washington's coast, as well as modeled estimates of likely bedrock movements associated with tectonic processes. A detailed description of our vertical land motion estimates can be found in **Appendix C**.

Notably, our approach also assessed the uncertainty in the vertical land movement estimates, so that we could estimate a probability distribution for the rate of vertical land movement. This made it straightforward to combine the absolute sea level rise and vertical land movement estimates to develop probabilistic projections of relative sea level rise at discrete locations on Washington's coastline.

CONCLUSIONS

This report provides an updated set of sea level rise projections for Washington State. The projections improve on previous work by incorporating the latest science, providing community-scale projections, and assessing the probability that sea level rise meets or exceeds a particular change in elevation.

The probabilistic projections are intended to better align with coastal risk management and planning. By providing likelihoods, users can select probabilities to align with a particular decision context or risk management approach. For example, planners might want to consider high-impact low-probability projections for decisions regarding critical infrastructure (e.g., a hospital), whereas the low-end or middle projections might be the best approach for situations where management can easily be adapted in the future (e.g., vegetation management).

Image credit: Fisherman in stormy weather in Ocean Shores, WA.
Photo by: Bernd Thaller, used under CC BY 2.0

Our new projections reflect the latest science on sea level rise and are an improvement over previous assessments. Over time, these will undoubtedly be updated as new science becomes available. Until that time, we recommend using these new projections for coastal impacts assessments within the state of Washington.

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