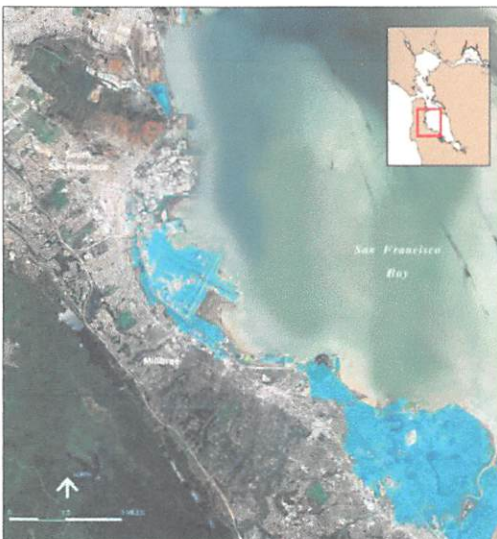


## Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future

As more and more states are incorporating projections of sea-level rise into coastal planning efforts, the states of California, Oregon, and Washington asked the National Research Council to project sea-level rise along their coasts for the years 2030, 2050, and 2100, taking into account the many factors that affect sea-level rise on a local scale. The projections show a sharp distinction at Cape Mendocino in northern California. South of that point, sea-level rise is expected to be very close to global projections; north of that point, sea-level rise is projected to be less than global projections because seismic strain is pushing the land upward.

Any significant sea-level rise will pose enormous risks to the valuable infrastructure, development, and wetlands that line much of the 1,600 mile shoreline of California, Oregon, and Washington. For example, in San Francisco Bay, two international airports, the ports of San Francisco and Oakland, a naval air station, freeways, housing developments, and sports stadiums have been built on fill that raised the land level only a few feet above the highest tides.

Sea-level change is linked to changes in the Earth's climate. A warming climate causes global sea level to rise principally by (1) warming the oceans, which causes sea water to expand, increasing ocean volume, and (2) melting land ice, which transfers water to the ocean. However, at regional levels, sea-level rise is affected by a number of additional factors. On the U.S. west coast, factors include regional climate patterns such as El Niño, which warm and cool the Pacific Ocean; the rising and sinking of land along the coast as a result of geologic processes such as plate tectonics; and proximity to Alaska glaciers, which exert a gravitational pull on sea water.



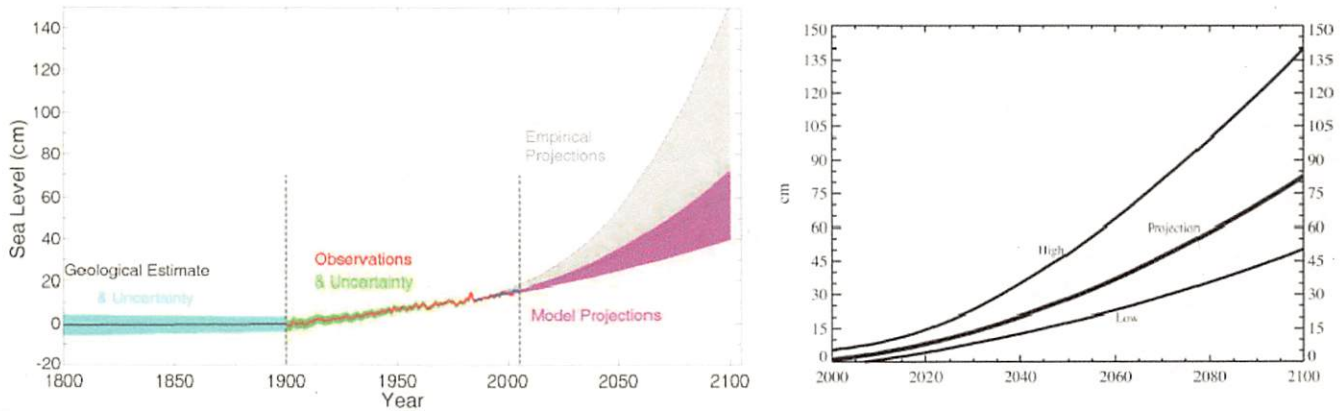
The San Francisco International Airport (center) and surrounding areas will begin to flood with as little as 40 cm (16 inches) of sea-level rise, a value that could be reached in several decades. Image courtesy Bay Conservation and Development Commission

In compliance with a 2008 executive order, California state agencies have been incorporating projections of sea-level rise into their coastal planning. This study provides the first comprehensive regional projections of the changes in sea level expected in California, Oregon, and Washington.

### Global Sea-Level Rise

Following a few thousand years of relative stability, global sea level has been rising since the late 19th or early 20th century, when global temperatures began to increase. The most comprehensive assessments of global sea-level rise come from the

Intergovernmental Panel on Climate Change (IPCC). Based on tide gage measurements from around the world, the IPCC estimated that global sea level rose an average of about 1.7 mm per year over the 20th century. Over the past 20 years of the century, precise satellite altimetry measurements and tide-gage records show that the rate of sea-level rise increased to about 3.1 mm per year, and it is projected to rise at an even faster rate in the future (Figure 1).



**Figure 1. Observed and projected sea-level rise.** After a few thousand years of relative stability, sea level began to rise along with global temperatures beginning in about 1900, as measured by tide gages (red line) and satellite altimetry (blue line). Projections of sea-level rise to 2100 in dark pink are from the IPCC and are based on global climate models that estimate the individual contributions to sea-level rise. Projections in gray are from Vermeer and Rahmstorf and are based on the observation that sea level rises faster as the Earth gets warmer. The projections from this report (right, beginning at a zero in the year 2000) fall between the two.

However, different projection approaches yield very different estimates. The IPCC projects sea-level rise using computer models (Figure 1, dark pink). An alternative approach is based on the observation that sea level rises faster as the Earth gets warmer (Figure 1, gray). Neither method accounts fully for the rapid changes in the behavior of ice sheets and glaciers that have been observed recently (see Box 2). The global sea-level rise projections in this report, which use models and extrapolations of historical trends and account for rapid changes in ice behavior, fall between those two estimates.

### Sea-Level Rise in California, Oregon, and Washington

Sea level is not uniform everywhere and is continually changing. A number of natural processes affect sea level at any given place and time—from tides that produce hourly changes to tectonic forces that take place over millions of years. Along the coast, sea level is measured relative to the land. Thus, factors that affect both ocean levels and land levels must be considered in projections of regional sea-level rise.

#### Regional Factors Affecting Ocean and Land Levels

Along the west coast of the United States, climate patterns such as the El Niño–Southern Oscillation affect winds and ocean circulation, raising local sea level during warm phases (El Niño) and lowering sea level during cool phases (La Niña). Large El Niño events can raise coastal sea levels by 10 to 30 cm (4 to 12 in) for several winter months.

The large mass of glaciers and ice sheets creates a gravitational pull that draws ocean water closer. As the ice melts, the gravitational pull decreases, ice melt enters

the ocean, and the land and ocean basins rise or sink (deform) as a result of this loss of land ice mass. These effects produce a distinct spatial pattern of regional sea-level change commonly referred to as a sea-level fingerprint. Ice in Alaska, Greenland, and Antarctica has a significant effect on the ocean in the northeast Pacific Ocean. The gravitational and deformational effects of melting from these three sources reduces the rate of relative sea-level rise, especially in northern Washington.

The melting and eventual disappearance of the ancient North American ice sheets has a different impact on sea-level rise that varies by location. The land is rising about 1 mm per year in northernmost Washington, which had been covered by an ice sheet; the land rise causes relative sea level to fall. However, in areas at the margins of the ice sheet and beyond, which includes the rest of Washington, Oregon, and California, the land is sinking about 1–2 mm per year, causing relative sea level to rise.

Human activities can have a significant effect on land height at the local level. For example, the extraction of water or hydrocarbons from under ground can lower surface elevations up to tens of centimeters per year if

**Box 2. Contribution of Melting Land Ice to Sea-Level Rise.** Since 2006, the ice loss rate from the Greenland Ice Sheet has increased, and, according to most analyses, the contribution of the Antarctic Ice Sheet to sea-level change has shifted from negative (lowering sea level by accumulating ice) to positive (raising sea level). Ice loss rates from glaciers and ice caps have declined over the same period, but not enough to offset the increases in ice sheet melt. Melting land ice is now the largest contributor to global sea-level rise.

fluids are not returned; however, these effects are too local to affect regional projections.

The most significant effect on regional land levels results from plate tectonics. Washington, Oregon, and northernmost California lie along the Cascadia Subduction Zone, where the ocean plate descends below the North American plate, causing the land to be pushed upward. Along the rest of California, the Pacific and North American plates are sliding past one another along the San Andreas Fault Zone, creating relatively little vertical land motion along the coast. In essence, it's a tale of two coasts: Global Positioning System (GPS) measurements show that north of Cape Mendocino, much of the coast is rising about 1.5–3.0 mm per year; south of Cape Mendocino, the coast is sinking an average of about 1 mm per year.

### Sea-Level Rise Projections for California, Oregon, and Washington

Projections of sea-level rise for California, Oregon, and Washington, which take account of both global and regional factors, are illustrated in Figure 2. For the California coast south of Cape Mendocino (labeled MTJ in the figure), the committee projects that, relative to 2000, sea level will rise 4–30 cm (2–12 in) by 2030, 12–61 cm (5–24 in) by 2050, and 42–167 cm (17–66 in) by 2100. These projections are close to global sea-level rise projections. However, for the Washington, Oregon, and California coasts north of Cape Mendocino, sea level is projected to change between –4 cm (–2 in, sea-level fall) and +23 cm (9 in) by 2030, –3 cm (–1 in) and +48 cm (19 in) by 2050, and 10–143 cm (4–56 in) by 2100.

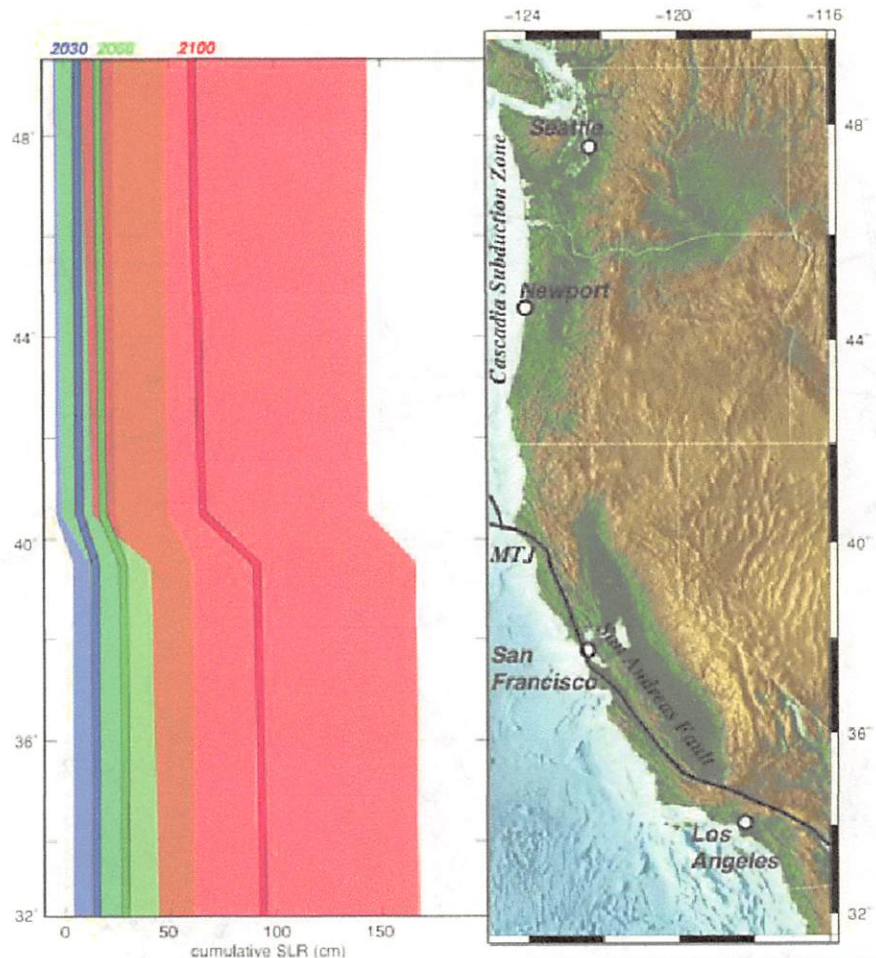
The seismic strain that is causing the land to rise north of Cape Mendocino is relieved every few hundred to 1,000 years by a large earthquake (magnitude 8 or greater), which causes parts of the coast to immediately drop and relative sea level to suddenly rise. The last one in the region occurred in 1700. If a large earthquake occurs, relative sea level could rise an additional 1–2 meters (3–7 feet) over projected levels north of Cape Mendocino.

At shorter timescales (2030 and perhaps 2050), models provide a reasonable representation of the future climate

system, and confidence in the global and regional projections is relatively high. By 2100, however, all projections have large uncertainties. The actual value of sea-level rise in 2100 will almost surely fall somewhere within the wide uncertainty bounds calculated by this report's authoring committee, although the exact value cannot be specified with high confidence.

### Sea-Level Rise and Storminess

Most of the damage along the California, Oregon, and Washington coasts is caused by storms—particularly the confluence of large waves, storm surges, and high tides during a strong El Niño. Understanding their additive effects is crucial for coastal planning. To date, there is no consensus about how climate change will affect the severity of storms in the northeast Pacific. A



**Figure 2. A Tale of Two Coasts:** Projected cumulative sea-level rise (in cm) shows a steep change at Cape Mendocino (labeled MTJ). The descent of the ocean plate along the Cascadia Subduction Zone has caused much of the land along the coasts of Washington, Oregon, and northernmost California to rise at about 1.5–3 mm per year, decreasing relative sea-level rise. South of Cape Mendocino, where the coast is slowly sinking at about 1 mm per year, projections are close to global projections. The slight slope in the projection curves from north to south reflects the sea-level fingerprint of melting Alaska glaciers, which lower relative sea level, especially in northern Washington.



High surf during a high tide at Neskowin, Oregon, in 2008. Image courtesy of Armand Thibault.

number of climate models predict that the North Pacific storm track will move north over the course of the 21st century, which could lessen storm impacts in southern California and increase impacts in Oregon and Washington. Several observational studies also have reported that the largest waves have been getting higher and that winds have been getting stronger over the past few decades. However, observational records are not yet long enough to determine conclusively whether these changes are occurring.

Even if storminess does not increase in the future, sea-level rise will magnify the adverse impact of storm surges and high waves on the coast. For example, a model using the committee's sea-level projections predicts that the incidence of extreme high water

events (1.4 m or 4.6 ft above historical mean sea level) in the San Francisco Bay area will increase substantially with sea-level rise, from less than 10 hours per decade today to a few hundred hours per decade by 2050 and several thousand hours per decade by 2100.

The natural shoreline can provide partial protection for coastal development against sea-level rise and storms. Coastal cliffs, beaches, and dunes take the brunt of storm waves and are therefore eroding over the long term. The net result of storms and sea-level rise is coastline retreat, with rates ranging from a few centimeters per year for cliffs to several meters per year for beaches and dunes. There is some good news with regard to marshes and mudflats, which protect inland areas by storing flood waters and damping wave height and energy. The frequent storms and associated floods in central and southern California potentially provide enough sediment for marshes to keep pace with the sea-level rise projected for 2030 and 2050.

**About this Study.** In 2008, Governor Arnold Schwarzenegger issued an executive order directing California state agencies to plan for sea-level rise and coastal impacts. The order also asked the National Research Council to assess sea-level rise in California. The states of Oregon and Washington, the U.S. Army Corps of Engineers, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey joined California in sponsoring this NRC study.

Read or purchase this report and locate information on related reports at <http://dels.nas.edu/besr>

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The National Academies appointed the above committee of experts to address the specific task requested by the sponsors. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.



For more information, contact the Board on Earth Sciences and Resources at (202) 334-2744 or visit <http://dels.nas.edu/besr>. Copies of *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; [www.nap.edu](http://www.nap.edu).

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