Sea Level Rise: Causes, Effects, and Policy Considerations in Washington

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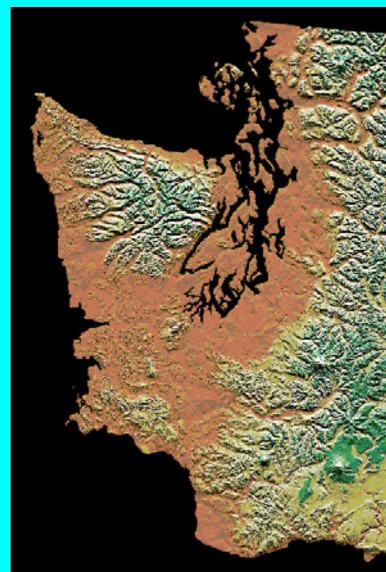
This morning I am going to talk briefly about some aspects of sea level rise and coastal management in Washington State in general and Puget Sound in particular.

I began studying sea level rise and its effects for the Washington Department of Ecology in 1988. We completed general technical studies on sea level rise and potential effects, on the role of vertical land movements in aggravating or alleviating sea level rise rates, and on the effects of sea level rise on coastal wetlands; we contracted for a policy alternatives study; and we gave a grant to the City of Olympia to conduct a municipal risk assessment; and we convened a sea level rise conference in 1989.

Since 1997 I have worked with the Climate Impacts Group at the University of Washington on coastal issues, and continue to do so since my retirement from the Dept of Ecology.

Climate & PNW Coastal Zone

- Sea Level Rise
  - Coastal erosion
  - Inundation
  - Other...
- Combined with increased winter precipitation
  - Bluff landsliding
  - Flooding



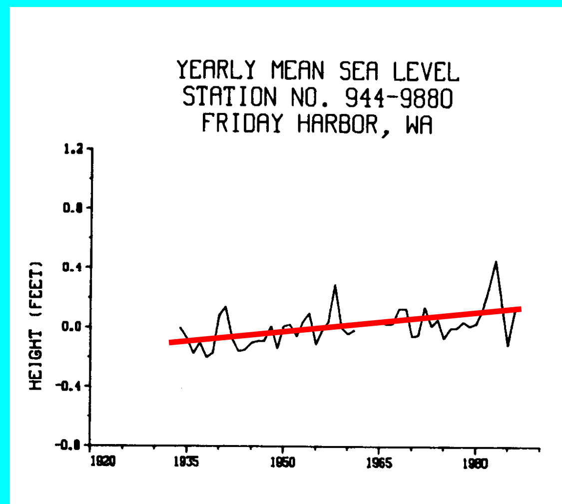
When we talk about climate change affecting the coastal zone, we often think only in terms of sea level rise and resultant coastal erosion and inundation. As soon as we begin looking at secondary and tertiary effects, though, we begin to discover issues like erosion into old coastal dump sites, sea water intrusion into coastal aquifers, impeded coastal flood drainage due to higher water tables, inundation of low-lying facilities, the interaction of increased winter rainfall with sea level rise to aggravate the existing problems associated with bluff landsliding, etc.

This presentation will summarize the nature of sea level rise and the projections for the future, and outline major effects. We don't have the time today to do more than scratch the surface.

We'll start by looking at the recent sea level rise trends in Washington State.

Friday Harbor sea level trend

From 1935 to 1999, water level at the Friday Harbor gage has been rising at about 1.24 mm/yr or 0.4 ft/century

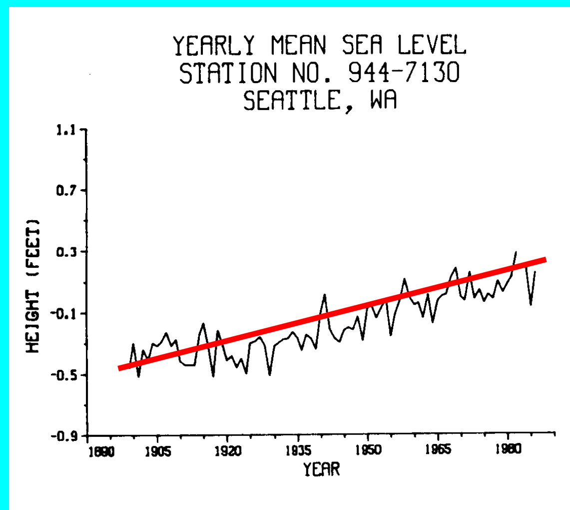


At Friday Harbor, the tide gage record since 1935, when the gage was installed, shows a local sea level rise rate of about 1.24 mm/year, or about 0.4 ft/century.

The annual variations in mean sea level you see here are typical of plots of tide gage records, and reflects a number of factors including weather, climate, and the solar and lunar cycles which drive the tides. Cumulatively, those solar and lunar cycles repeat over an 18.6 year period. That 18.6-year cycle makes it difficult to assess changes in sea level trends.

Seattle sea level trend

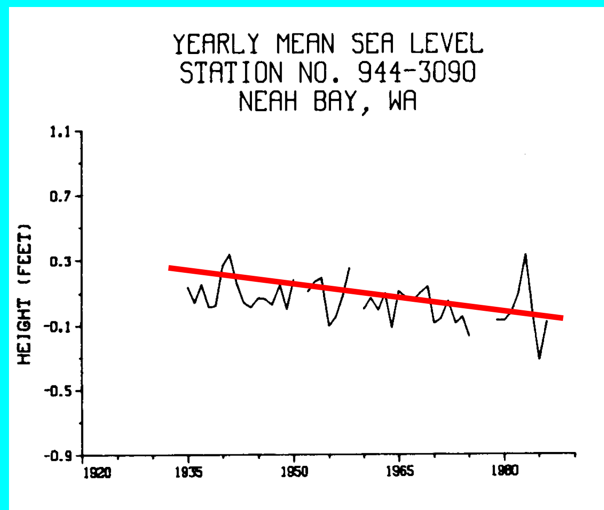
From 1899 to 1999, water level at the Seattle gage has been rising at 2.0 mm/year or about 0.7 foot/century



At Seattle the local long term trend illustrated by the tide gage record is 2.0 mm/year or about 0.7 foot/century – nearly double the rate at Friday Harbor.

Neah Bay sea level trend

From 1935 to 1999, water level at the Neah Bay gage has been trending down at -1.41 mm/year or about -0.5 ft/century.



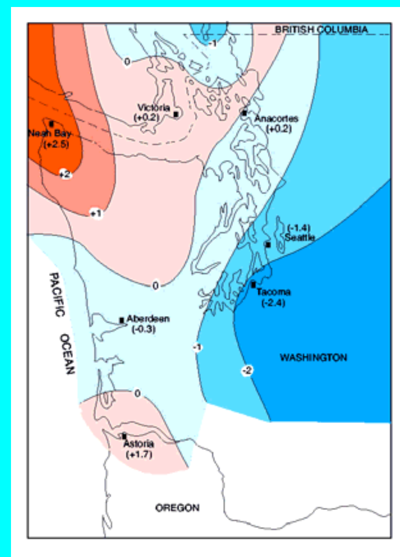
At Neah Bay, on the other hand, the local sea level trend is -1.41 ft/year or about -0.5 ft/century.

So what's going on?

First — in looking at these tide gage records, and the plots of water level change — we're talking about relative sea level change, that is, change relative to the local coast line which itself may be moving vertically.

Vertical Land Movement...

- … alters sea level rise rates...
    - Subduction zone tectonic forces ‘wrinkle’ the land surface:
    - Uplift occurs on much of the Ocean coast
    - Subsidence occurs in most of Puget Sound
    - Rates uncertain or variable

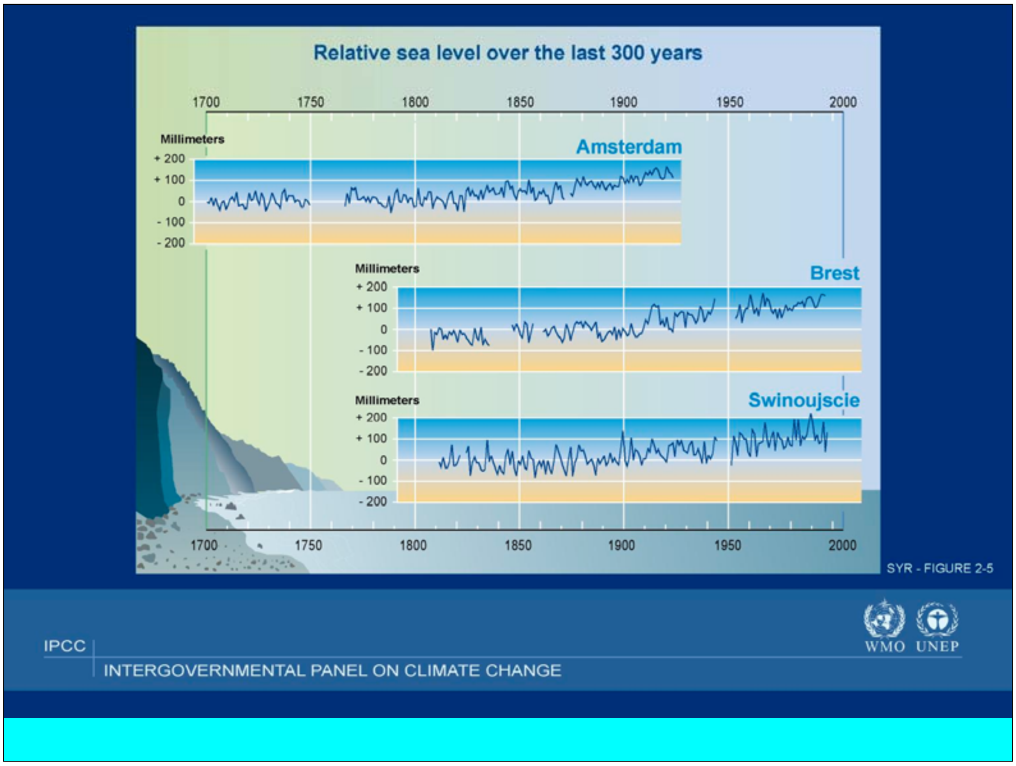


Vertical land movements of many types and causes are common.

In western Washington, for a few thousand years following the retreat of the glacier which once filled the present Puget Sound Basin, and the removal of that weight, the land was rebounding relatively rapidly at the same time global sea level was rising rapidly.

Presently, any remaining rebound in the Puget Sound basin is masked by crustal warping. The red tint indicates areas uplifting; the blue tint areas that are subsiding. Despite those nice, clear lines, the data are rather approximate due to the difficulty of making this kind of measurements and comparisons.

The Puget Sound basin is subsiding at rates possibly as great as 2.0 mm/year while the Pacific Ocean coast is uplifting at rates up to 2.5 mm/year. These vertical land movements are reflected in the tide gage records we’ve been looking at. The map is idealized, and based on research through the late 1980s. More recent research shows some differences in the rates of vertical movements, especially in the Puget Sound Basin. Presently, I’m still in the process of trying to make sense of the three principal research papers and don’t have complete confidence in any of them.



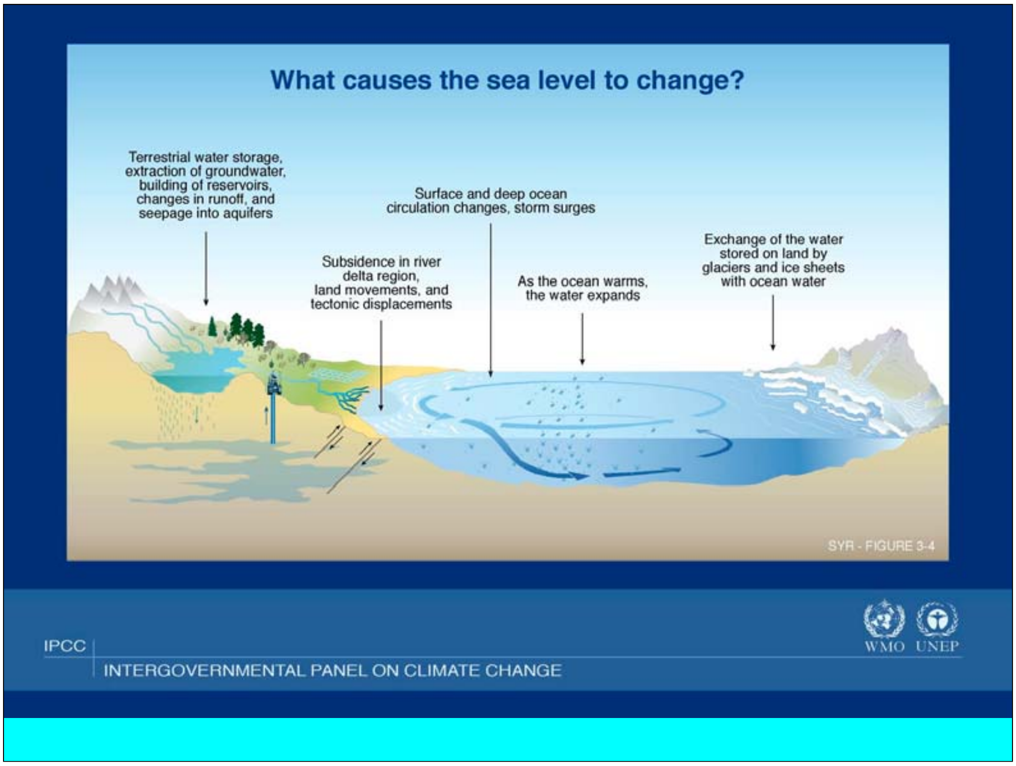
Globally, sea level rise is reported to be in the range of 1.0 to 2.5 mm/year depending on how and where and when the measurements are made. This range is about 0.3 to 0.8 ft/century.

Sea level tended to be more-or-less stable through the late 19th Century, after which time it began to rise.

Because there are few tide gages on the planet which have been in place for more than 50 years, it’s difficult to get a reliable, accurate global picture of sea level trends.

Generally, a tide gage record of at least 25 years is necessary for a sea level trend analysis. What tide gages there are, are unevenly distributed, with most in the Northern Hemisphere, and few in mid-ocean.

During the past decade a satellite network has been in development to acquire sea level data globally. The Topex/Poseidon satellite was launched in 1992 and is part of an on going program to measure the world's oceans from space. One of the current satellites, Jason-1, can measure sea level to 3.3 cm. This cannot compare with the accuracy of tide gage data, but does extend sea level measurements to the open ocean.



Sea level change is composed of a number of factors.

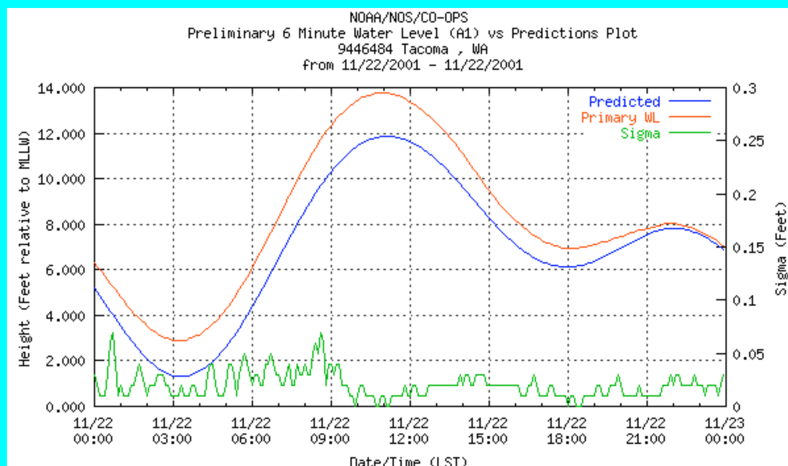
Heat exchange from the atmosphere warms ocean water, causing it to *expand*, thus contributing to sea level rise. In time the heat absorbed by surface waters propagates into deeper water causing further expansion.

The *addition of water* to the oceans by the melting of glaciers, ice fields, and snow fields also contributes to sea level rise. At the same time some portions of glaciers and snow fields are melting, other portions are accumulating new snowfall – the result is the *mass balance* you may hear about.

Sea level rise is *mitigated* by the many diversions of water flowing into the sea — impoundments in reservoirs large and small, as well as agricultural irrigation. The cumulative effect of these many small diversions is substantial and on-going.

Ocean currents transfer heat gain from the atmosphere to the ocean surface in an uneven manner leading to differential warming, expansion, and sea level change patterns. A Canadian climate modeling group developed differential sea level rise scenarios for the major ocean basins in 2000, and since then other modelers have also done so, but with differing results.

Daily Variation



Short term low pressure cells allow water level to rise: up to 2.0 feet on 22 Nov 2001 at Tacoma

Short term variation in sea level can be substantial.

In this example from the Tacoma gage on a day of exceptionally low barometric pressure the recorded tide level (the red line) was running about two feet above the predicted tide level (blue Line) at the mid-day high tide.

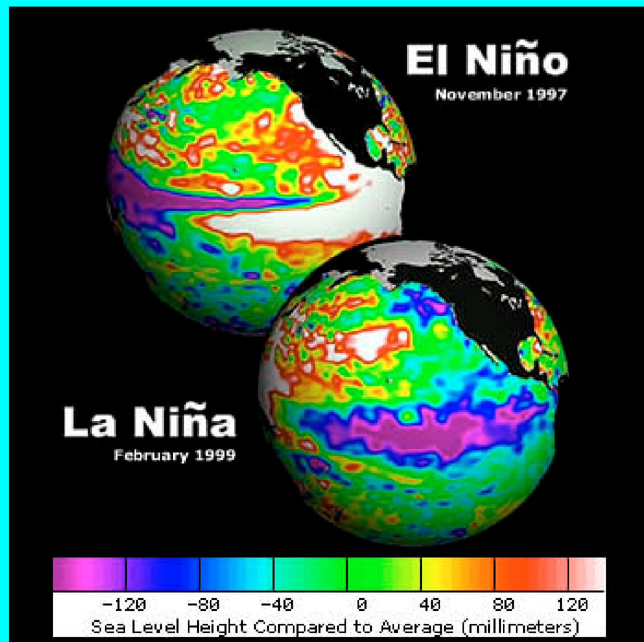
To visualize how this happens, think of the atmosphere as having weight which pushes down on the ocean (which it does). The barometric pressure is a measure of that weight. When there’s less pressure, or weight, in one place, and more pressure, or weight, in another place, the high pressure area forces the ocean water down, and the low pressure area allows water to flow into that area and rise.

This is partly why low pressure storm cells on the coast can result in unusually large amounts of damage; this is what happened on the Gulf Coast in 2005 during hurricanes Katrina and Rita.

In the Pacific Northwest, it’s not necessary for a violent storm to come ashore accompanied by a low pressure cell to cause damage. If waves propagated by a distant storm in the Pacific Ocean come ashore at a time of low barometric pressure we can also experience greater storm damage than would occur if only one factor had occurred.

Annual Variation

- 1997-98: Mean sea level 1.31 ft higher
- 1982-83: Mean 1.04 ft higher



Longer term sea level variation in the eastern Pacific is associated with the El Niño - La Niña (aka ENSO or El Niño Southern Oscillation) cycles. Throughout an El Niño winter, the sea level is typically above the predicted tide levels for an extended time. The cause is partly due to barometric pressure shifts over the Pacific Ocean basin and a resultant movement of ocean water from the west Pacific to the east Pacific.

During El Niño, above average sea levels (red and white on the globe) are seen in the eastern Pacific Ocean near South America. Below average sea levels (blue and purple) occur simultaneously in the western Pacific.

During La Niña periods, sea level heights are lower than average (blue and purple) in the eastern Pacific Ocean and higher than average (red and white) in the western Pacific.

There's some thought that ENSO cycles could become more frequent and or stronger as a result of global climate change.

1997-98 mean water level at Toke Point tide gage: up to 1.31 ft above monthly mean, and up to 0.72 ft above monthly high.

1982-83 mean water level at Newport tide gage: up to 1.04 ft above monthly mean, and up to 0.62 ft above monthly high.

Coastal Erosion

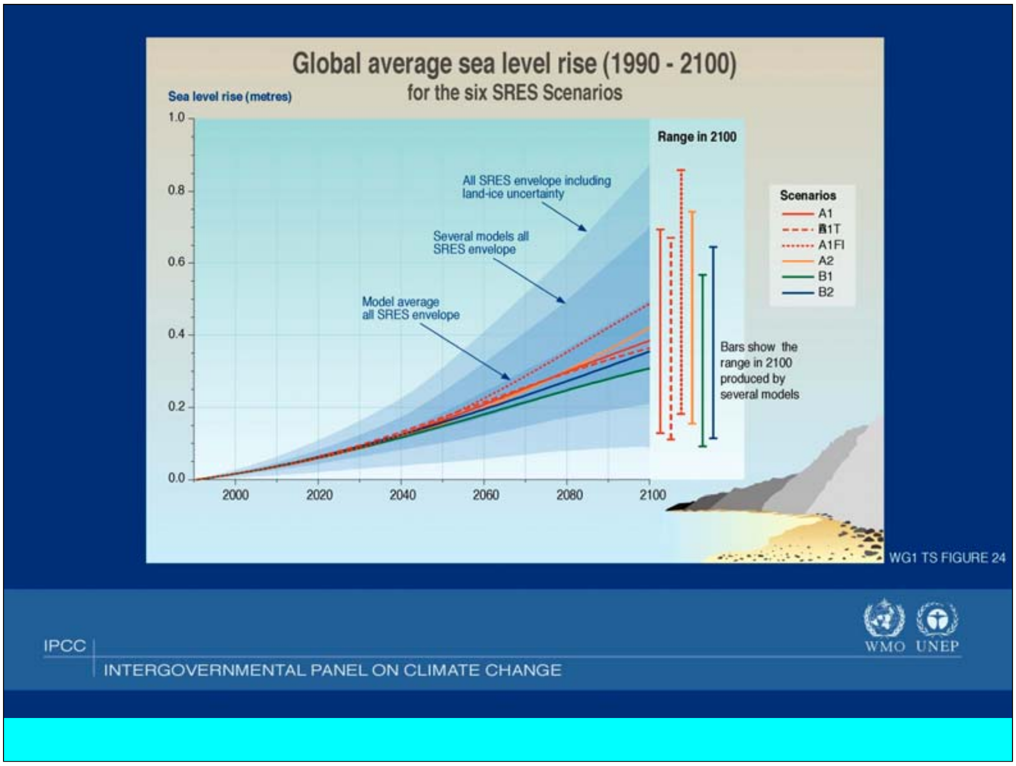
Point Brown, Ocean Shores — 1997 - 98

Here we're looking at some beach erosion which occurred during the El Niño of 1997-98 at Ocean Shores. Prior to the onset of this erosion the line of the beach ran straight to the jetty.

During the winter of 1997 - 1998 we experienced a fairly substantial El Niño with typically higher tides for many months. During this time there were a number of storms which resulted in substantial beach and dune erosion in the 0.3 mile north of the North Grays Harbor Jetty, with lesser erosion tapering off over an additional 1.2 miles. In that southerly 0.3 mile, one new condominium and an older condominium complex were threatened. After much regulatory debate the condominium owners' associations were permitted to build an armored beach fill to protect the structures. This was a very controversial issue. At least one, maybe two, of the condominium buildings had been constructed without the required shoreline permit. By the time construction commenced the beach erosion had cut through the primary dune to within a few tens of feet of the buildings.

On the evening on February 2 - 3, 1998, a strong storm came ashore causing more beach erosion and flank erosion up to 50 feet at the ends of the armored beach fill. That afternoon we flew over the area; this photo was taken at 3:50 pm when the tide was ~ 8.9 feet (MHHW = 9.4 ft).

Since then, the El Niño has passed, and normal beach-building processes have restored the beach here.



The global average sea level rise scenarios in common use are mostly based on the model developed by the IPCC — the Intergovernmental Panel on Climate Change — which in turn are based on IPCC's atmospheric change models, which in turn are based on assumptions about future energy use efficiencies, levels of economic activity, population growth, and public policy choices.

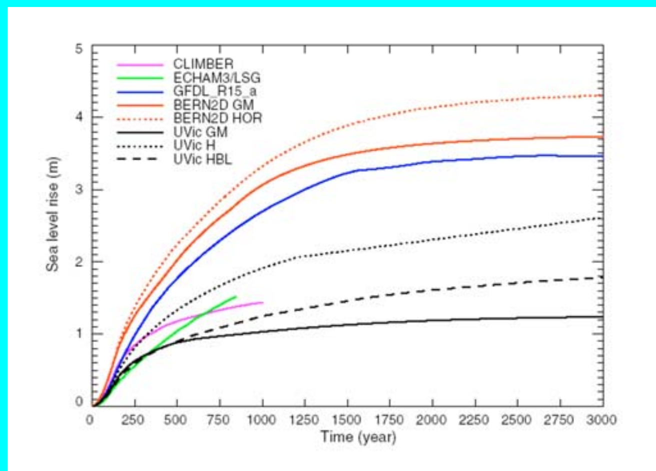
Please note what appear to be error bars on the right side of the graph. They represent the range of modeling results based on different assumptions. The mid-range results are not necessarily more likely to occur than modeling results at the extremes.

By way of comparison, the most prominent sea level rise scenario in use in late late 1980s (by the US Environmental Protection Agency) indicated 0.5 to 3.5 m of rise where these current IPCC scenarios indicate 0.2 to 0.7 m rise by 2100.

Finally, the sea level rise curves keep rising after 2100 – they don't just suddenly level off.

No one of these scenarios is "better" or more reliable than any other. That makes sea level rise policy response more complicated, requiring a policy choice of how much – or little – risk to plan for.

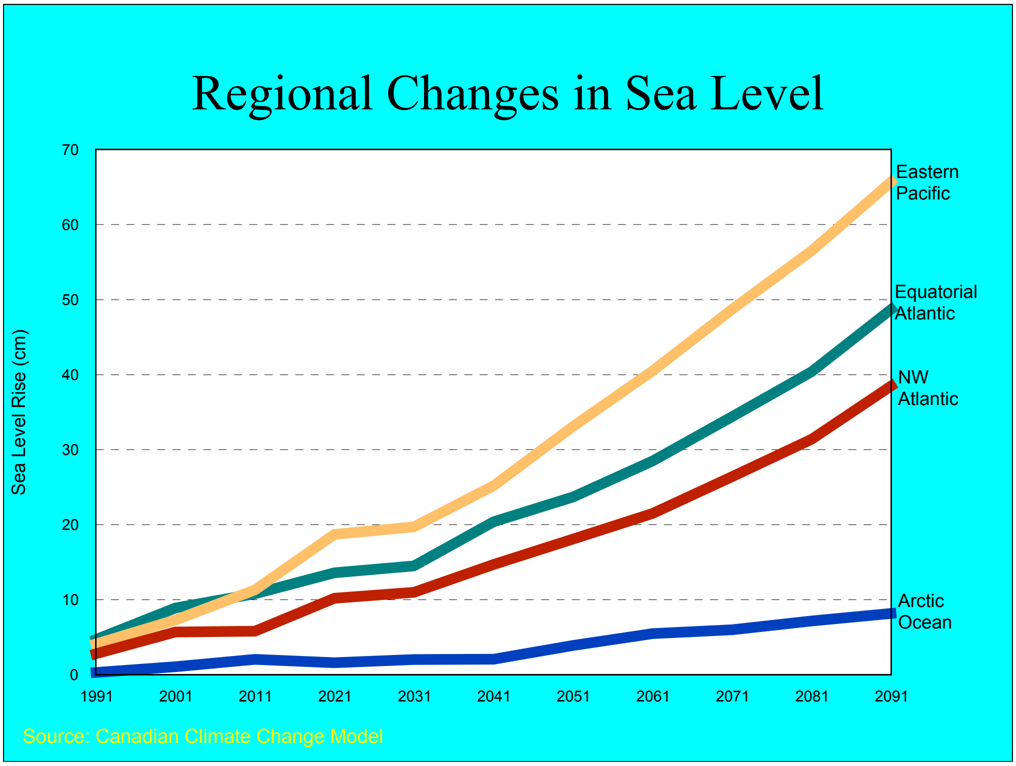
Long-range Scenarios



Sea level rise is projected to continue for many centuries with up to 4 m/13 ft rise

This graphic represents the IPCC's long term projections which range from 1 meter to 4 meters of rise over 500 to 1500 years.

Now…these sea level rise scenarios are from the IPCC's most recent published report, the Third Assessment Report of 2001. A Fourth Assessment Report is expected to be published beginning February, 2007. There is much speculation that the 4AR report sea level rise scenarios for 2100 will span up to 2 meters.



Canadian sea level rise modelers (as well as others) have taken the IPCC's global average approach an additional step.

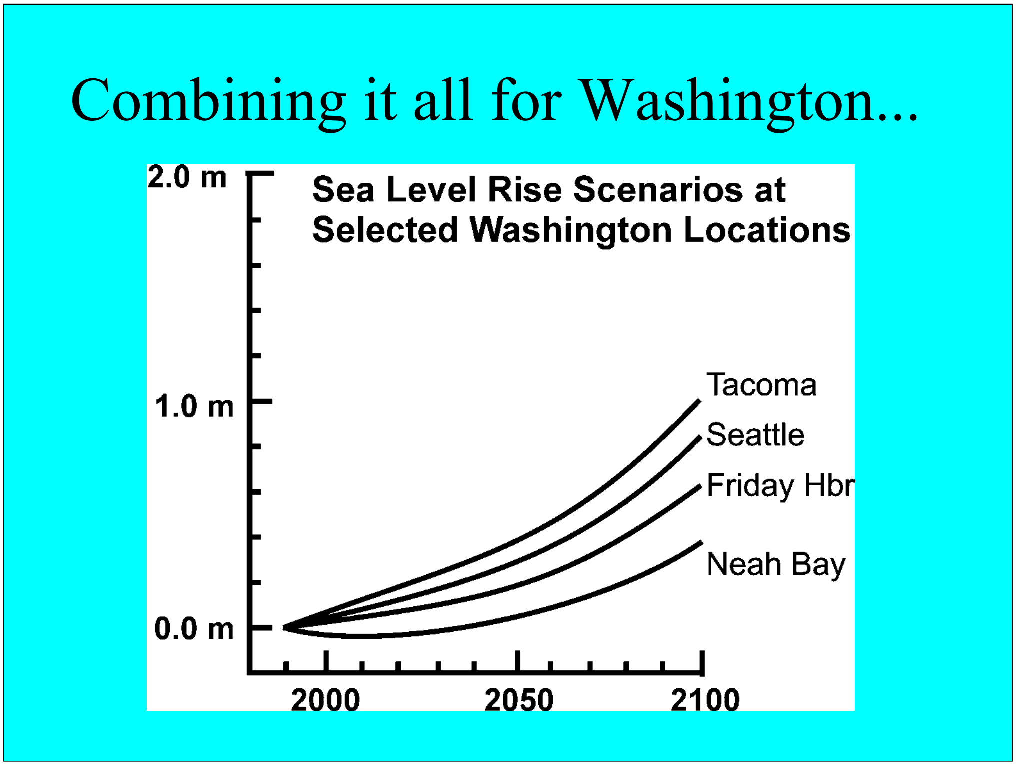
They have modeled sea level rise variation in the different major ocean basins based on assumptions about thermal expansion and atmospheric pressure patterns, plus ocean circulation patterns.

In this graphic from their report, the red curve for the North Atlantic also happens to approximate the IPCC's mid-range scenario.

The yellow curve for the eastern Pacific indicates that sea level rise on the eastern shore of the Pacific — including the Pacific Northwest — could be half again as much as the global average, or 160 percent of the global average.

As one might expect, other modelers have come up with different variations on regional sea level rise scenarios based on the modeling assumptions they have chosen to make. More research is necessary in this area.

A choice to incorporate regional ocean basin differences in sea level change — or not — introduces yet an additional layer of complexity to the public policy choices and decisions.



If we combine the global scenarios, and the ocean basin scenarios, with apparent vertical land movements in Washington State, we get a set of differential sea level rise curves for selected locations in Washington.

Remembering that sea level rise at Friday Harbor is at an area of low or no vertical land movement, we'll use that as our baseline.

Sea level could be expected to rise a bit more rapidly at Seattle, and more rapidly yet at Tacoma where the ground is also subsiding, but at a higher rate.

The existing rate of land uplift at Neah Bay would continue to exceed the rate of sea level rise for a few more decades before acceleration of sea level rise overtakes uplift and sea level rise becomes evident at Neah Bay.

Don't forget — there are a lot of assumptions in this stack of scenarios, and these are not predictions as we normally think of the term; they are scenarios. The term "scenario" is a way of reminding ourselves that we're dealing with a measure of uncertainty based on our assumptions about the future.

Plus — these data result from using the mid-range scenario. The actual sea level change by 2100 could be lower or higher than these mid-range scenarios. So far as we know now, there is an equal probability of any of the scenarios occurring. Lower sea level rise scenarios are not more likely; higher sea level rise scenarios are not less likely. The mid-range scenario is not most likely – it's just the one that's most often applied.

Effects and Consequences

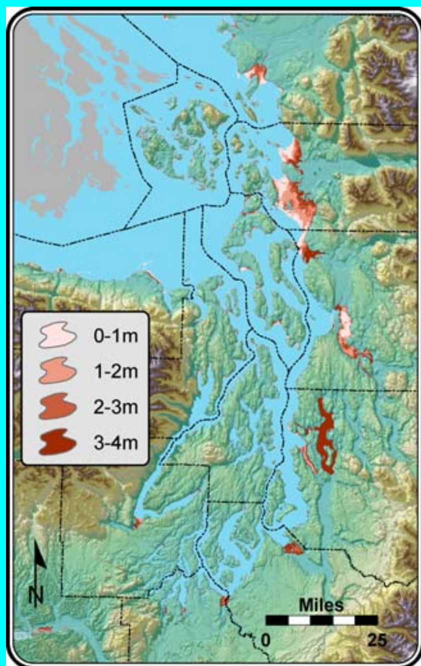
- Inundation and Flooding
  - Olympia central business district & port
- Coastal Erosion
  - Low bank, no bank
  - Bluff land sliding
- Sea Water Intrusion
  - McAllister Springs (City of Olympia)
- Habitat Conversion
  - Nisqually delta & lower valley

Inundation and flooding is an obvious effect of sea level rise and we'll be looking at a study of the Olympia central business district and port peninsula as a representative example.

Coastal erosion, as we saw in the example of El Niño-induced coastal erosion at Point Brown is another obvious effect. Bluff landsliding will be a likely problem throughout Puget Sound.

Sea Water intrusion of the City of Olympia's water supply at McAllister Springs was a surprise result of the City of Olympia study. We don't have time to go into that, but the City is working to develop new well fields not at risk.

The National Wildlife Federation is in the process of modeling the effects of sea level rise upon Puget Sound coastal marshes. We are having difficulties adapting the computer model, developed for Atlantic and Gulf coast marshes to Pacific Northwest conditions. We expect the final report to be published in a few months. This, by the way, makes for an instructive case study in the pit falls inherent in modeling studies.

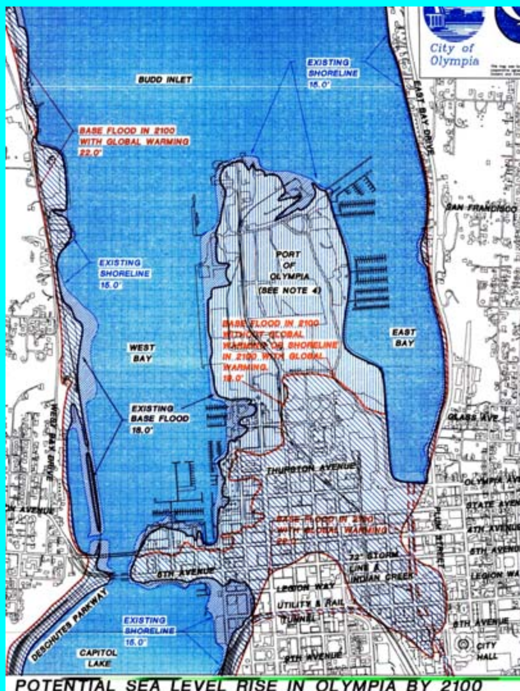


Puget Sound DEM Modeling

- Nooksack Delta
- Samish Delta
- Skagit-Stillaguamish
- Snohomish Delta system
- Lake Washington
- Duwamish Waterway
- Port of Tacoma
- Skokomish Delta
- Thurston County
  - Mud Bay
  - Olympia
  - Nisqually Delta

This 4-step sea level rise modeling by the Climate Impacts Group was designed to identify the locales most at risk from substantial sea level rise resulting from melting of the Greenland and Antarctic icecaps.

Notably, at 6 feet for sea level rise, Lake Washington is affected.



Olympia Study, 1993

- Vertical datum (0.0 ft) = MLLW
- Existing shoreline = 15.0 ft (~ OHWM)
- BFE = 18.0 ft
- Base SLR = 1ft/Cent.
- Accel. SLR = 4ft/Cent.

The first sea level rise effects study was completed by the City of Olympia in 1993. This was prior to the GIS era, so they were using an engineering design software package, AutoCAD.

My first point here is the choice of modeling datums and scenarios. Their base was not mean sea level as is so commonly used, but rather an approximation of Ordinary High Water.

Second, they modeled not just static sea level rise, but also its effect on the Base Flood Elevation (the coastal 100 year event).

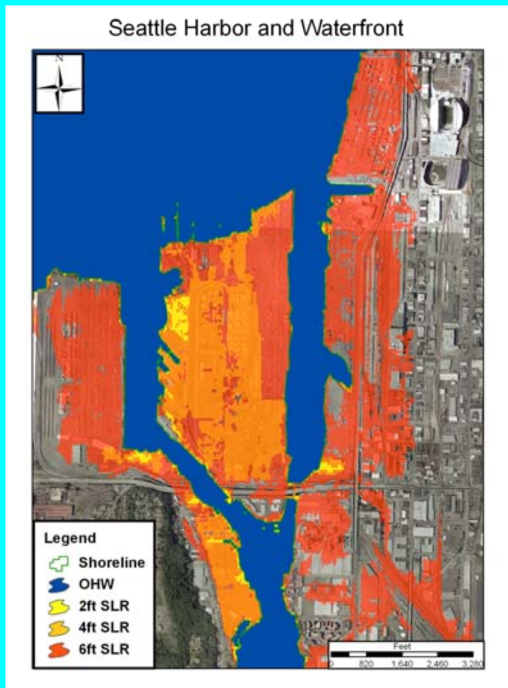
The modeling scenario was four feet by 2100, including land subsidence. Today, that might be more like three feet, but four feet would not be an unreasonable alternative scenario. Regardless, a four foot rise in sea level would occur eventually.

Existing (1990) shoreline: ordinary high water, or ~15.0 ft mllw

The purple line represents the 1990 Base Flood Elevation, ~18.0 ft, or highest recorded tide, and “100 year flood”

The orange line represents the Base Flood Elevation in 2100, ~19.0 ft due simply to local subsidence, or the shoreline in 2100 with accelerated sea level rise.

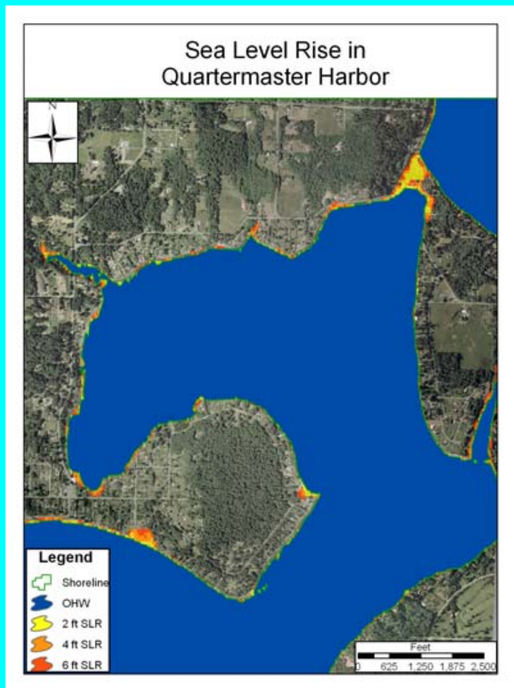
The red line represents the Base Flood Elevation in 2100, ~22.0 ft with accelerated sea level rise.



Seattle DEM Modeling, 2007

- Vertical datum (0.0 ft) = NAVD88
- Existing shoreline = 10.25 ft (~ OHWM)
- BFE = ~15 ft.

Sascha and I have begun to experiment with Digital Elevation Model-based sea level rise modeling. This is an example from Sascha's Seattle model focused on Harbor Island and the lower Duwamish Waterway.



Vashon-Maury DEM Modeling, 2007

- Vertical datum (0.0 ft) = NAVD88
- Existing shoreline = 10.36 ft (~ OHWM)
- BFE = ~14 ft

This is a detail from the Vashon-Maury Island model showing Quartermaster Harbor and The Portage connecting the two islands.

For the most part, the Vashon-Maury Island shore is backed by bluffs, so inundation is a minor problem in most areas.

The Portage between the two islands is low and could be be inundated at high tide by a two-foot sea level rise.

SLR Response

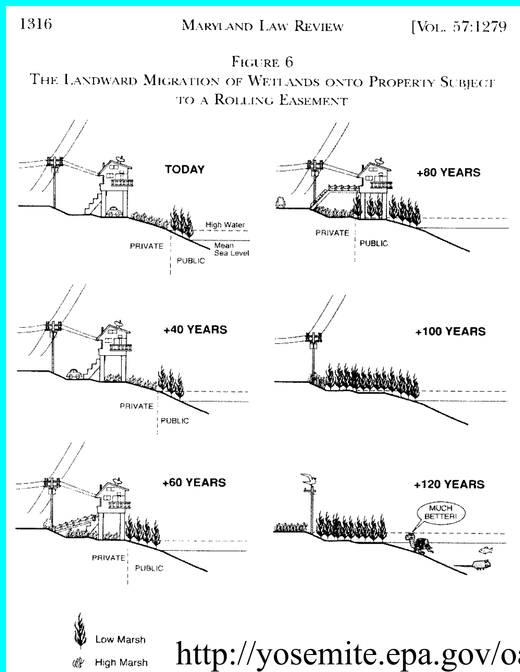
- We respond to flood hazards by linking *what's* at risk with the *probability* of flood risk, e.g. higher risk situations are managed by applying progressively lower probability, higher severity events (e.g. 100 year, 500 year event).
- We could respond to SLR hazards by associating what's at risk with the severity of the SLR scenario, e.g. higher risk situations are managed by applying progressively more aggressive SLR scenarios.

Dealing with the uncertainty of sea level rise has acquired a mystique of difficulty — difficulty in both a public policy context, and a planning and engineering context. Yet we've learned to deal with that kind of uncertainty in other policy and engineering settings.

When we design structures subject to flood hazard we have adopted the concept of the design storm or design event. That's the so-called 100-year flood, for example. Actually that term is misleading. A so-called 100-year flood is really a flood event for which there is a 1% chance of occurrence *each* year.

For a situations where more is at risk on rare occasions we'll rarely use the 500 year event. The City of New Orleans was protected by 100 year event structures – but you see how much good that did. Where we use the 100 year event, the Dutch use a 4,000 year to 10,000 year even as their design criteria for their coastal defenses.

The same type thinking could be applied to sea level rise response. We just need to reach a social consensus on this, and what the parameters might be.



Rising Seas, Coastal Erosion, and the Takings Clause: How to Save Wetlands and Beaches Without Hurting Property Owners. James G. Titus. 1998. Maryland Law Review 57 (4): 1279-1399.

http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsSLRTakings.html

We know of no sea level rise response legislation or regulations being implemented in the United States.

The principal examples come from Australia and New Zealand — nations where the coast is predominately in public ownership.

Jim Titus at the US Environmental Protection Agency in the 1990s was funding and carrying out research on sea level rise response. He’s been on a short leash since 2001, but oddly, his old sea level rise web site at EPA is still up.

His proposal, depicted here, illustrates a ‘rolling easement’ concept as a low-cost alternative to the purchase of development rights before development, or the buy-out of damaged structures.

In all its permutations, this is too complex to get into in the time we have. If you’re interested in these concepts I do encourage to acquire a copy of his Maryland Law Review article as a download from the EPA website.

Coastal Management Policy

- Shoreline Management Act
  - Local Shoreline Master Programs
- Growth Management Act
  - Local Geologic Hazards Critical Area
- Floodplain Management Act
  - Local Comprehensive FCM Plans
- Puget Sound Plan
- Aquatic Lands Management Act

As you know, coastal management policies in Washington State are scattered through a number of state laws, a few of which are listed here.

There is no explicit mention of sea level rise in any of these laws. Sea level rise is mentioned only in the implementing regulations for Critical Areas Ordinances required by the Growth Management Act. And that's only a suggestion that a CAO should – not shall – address sea level rise.

In the early 1990s, while at the Dept of Ecology, I contracted with Battelle Institute for a study of Sea Level Rise Policy Alternatives. That project precede the Growth Management Act, so it has limited specific application. The conceptual approaches are to varying degrees still valid. The reports are now out of print but I can provide them as Adobe Acrobat files.

In the end, though, this is a public policy decision for our elected officials — it's not a simple technical decision to be made by agency staff.

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