

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

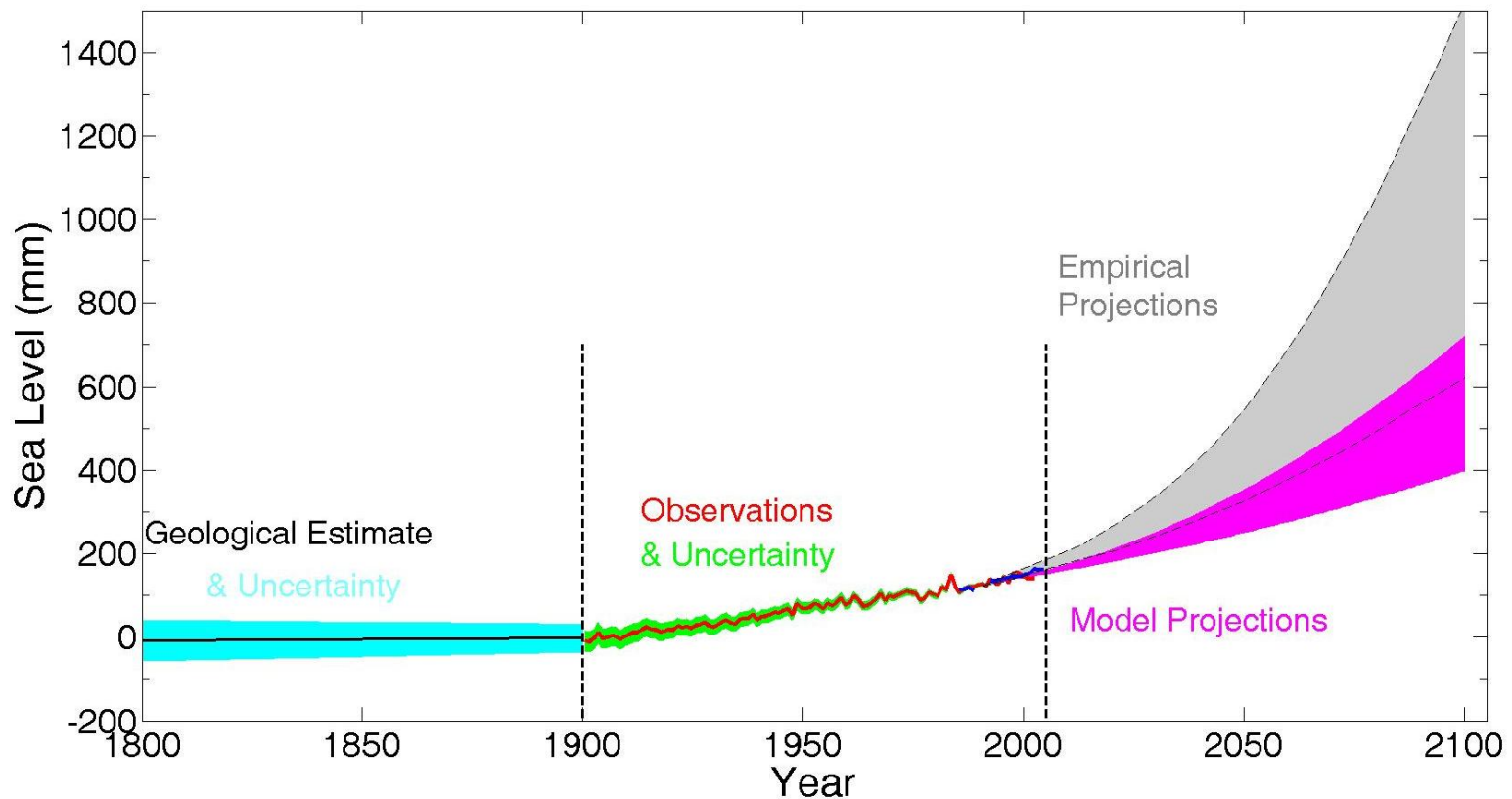
Robert A. Dalrymple
Committee Chair and Johns Hopkins University

June 20, 2012

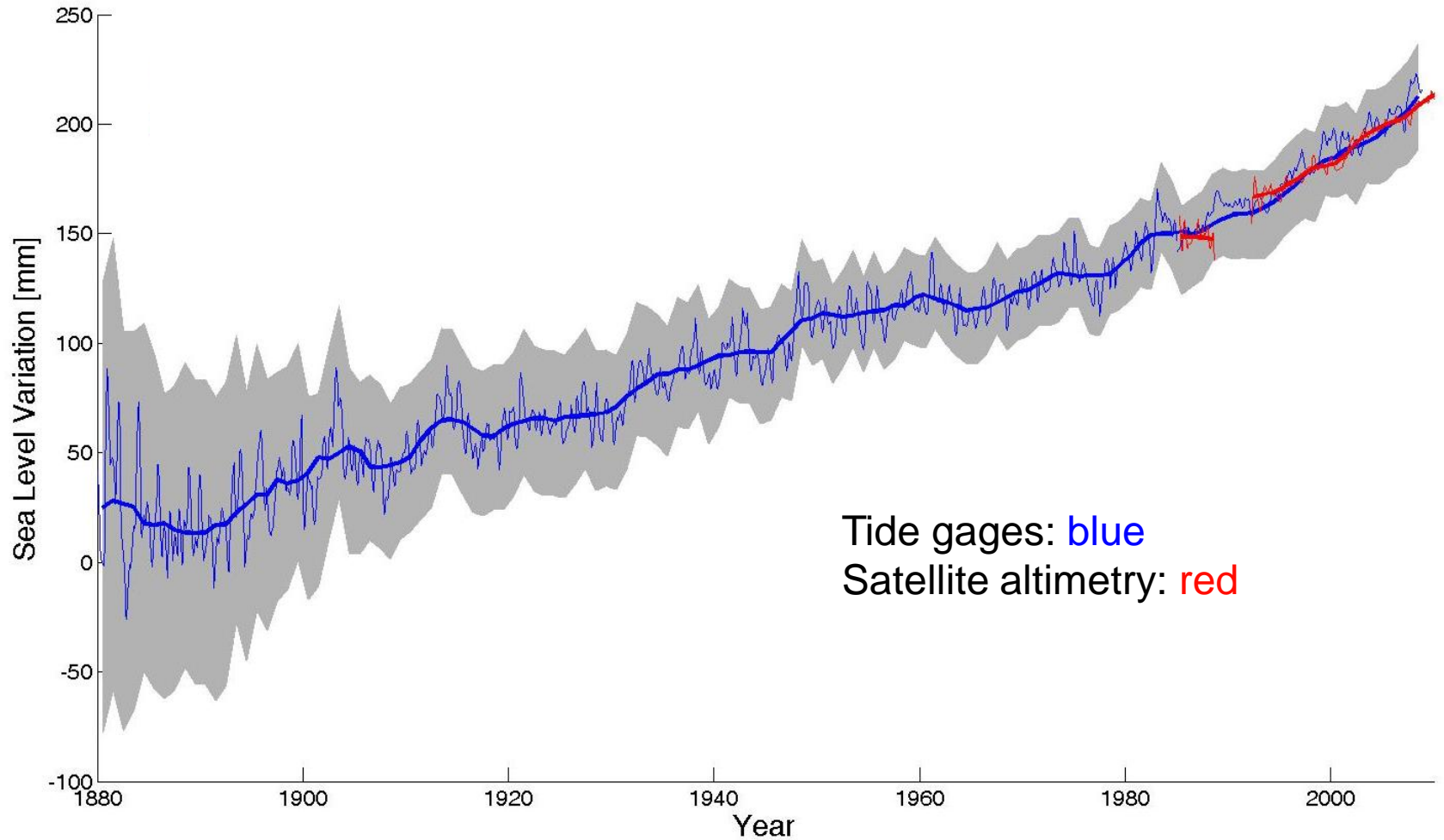
Global sea level is rising and is projected to rise at higher rates in the future

1.7 mm per year over 20th century (from tide gages)

3.1 mm per year since 1993 (from satellites & tide gages)



Historical Global Sea-Level Rise





Rising seas increase coastal erosion, shoreline retreat, and wetland loss; increases the risk of coastal flooding, and increases coastal damage from storms

Origins and Scope of This Study

- 2008 California Executive Order
 - Directed state agencies to plan for sea-level rise and coastal impacts
 - Asked the National Research Council to assess sea-level rise in California
- The states of Oregon and Washington, NOAA, USACE, and USGS joined California in sponsoring this NRC study

Committee Charge

Task 1. Estimate the contributions to global sea-level rise and project global sea-level rise for 2030, 2050, and 2100

Task 2. Estimate the contributions to regional sea-level rise and project sea-level rise for California, Oregon, and Washington for 2030, 2050, and 2100

2a. Examine any changes in storminess and how it would affect regional sea-level rise

2b/c. Examine how sea-level rise affects the shoreline and protection provided by habitats and the natural shoreline

Committee

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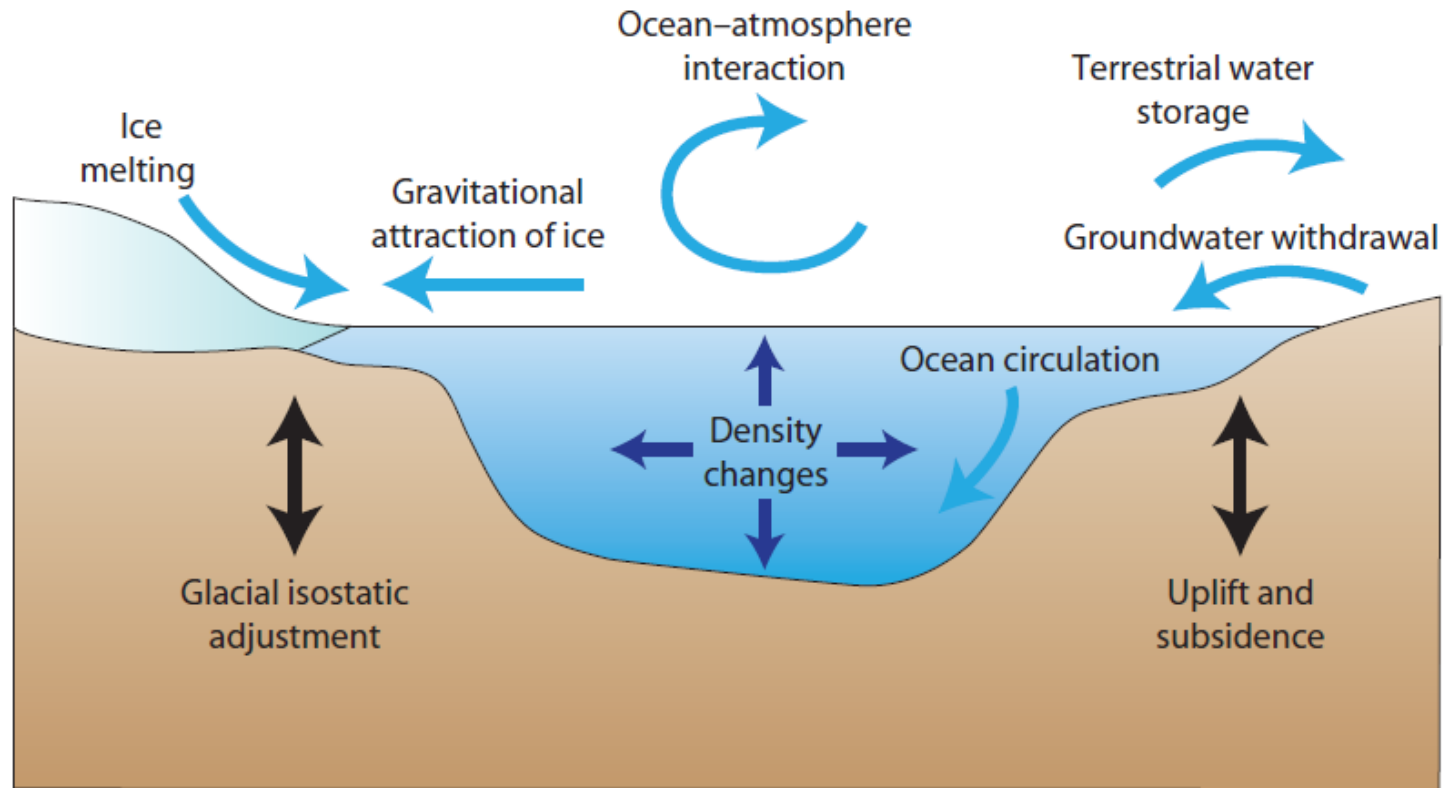
C.K. Shum, Ohio State University

Anne M. Linn, National Research Council

Task 1: Global Sea-Level Rise

- Estimate the major contributors to global sea-level rise
- Make projections of global sea-level rise for 2030, 2050, and 2100

Components of Global and Regional Sea-Level Rise



Sea level at a particular place can be higher or lower than the global mean due to regional effects

Causes of Global Sea-Level Change

A warming climate causes sea level to rise by:
warming the oceans, which causes sea water to expand, increasing ocean volume
melting land ice, which transfers water to the ocean

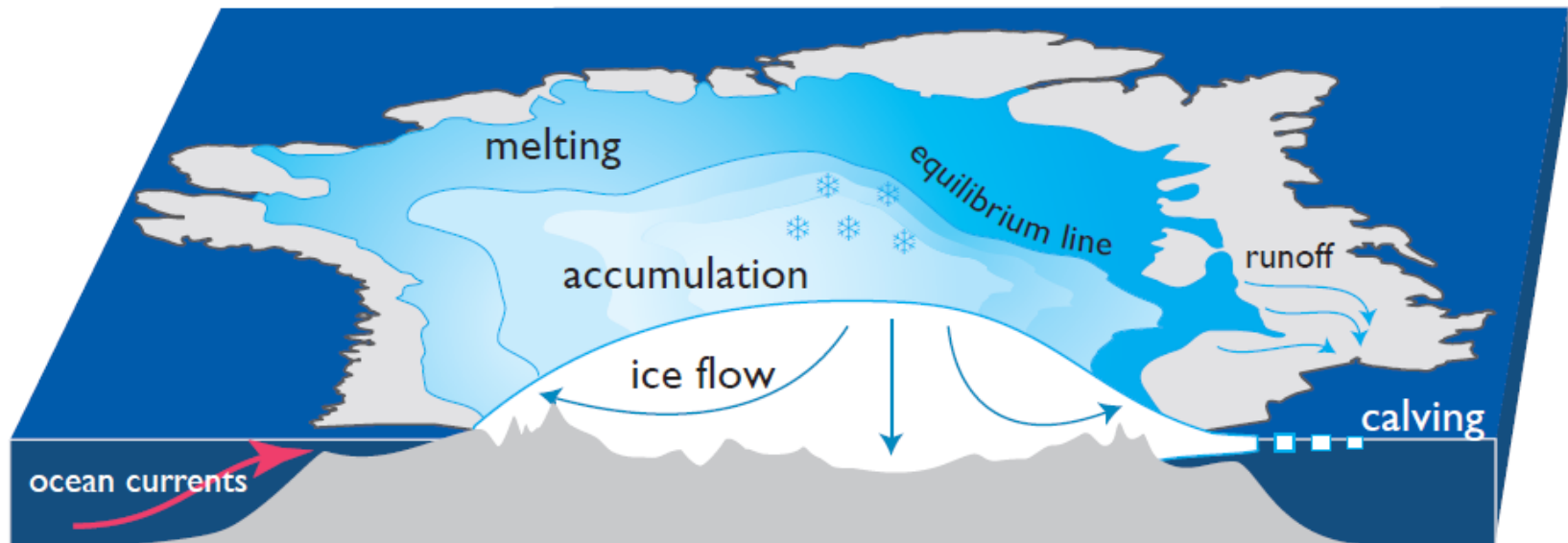
Human activities affect sea level by
withdrawing water from aquifers, which eventually reaches the ocean, causing sea level to rise
storing water that would have reached the ocean behind dams (sea-level fall)

Assessment of Components of Global Sea-Level Rise Since IPCC (2007)

- Thermal expansion of ocean water
Correcting biases discovered in ocean temperature measurements decreased estimates of the contribution of thermal expansion to about 35%
- Ice melt from ice sheets, glaciers, and ice caps
Ice loss rates are variable, but increasing overall, raising the land ice contribution to about 65%
- Groundwater withdrawal and reservoir storage
Uncertainties remain large, but the net contribution is small (a few %)

Contributions from Cryosphere

Ice dynamics: Rapid changes in ice sheets and glaciers as melting occurs



Max thickness: 4800 m in Antarctica; 3000 m in Greenland
57 m SLE; 7 m SLE

Methods for Making Global Projections

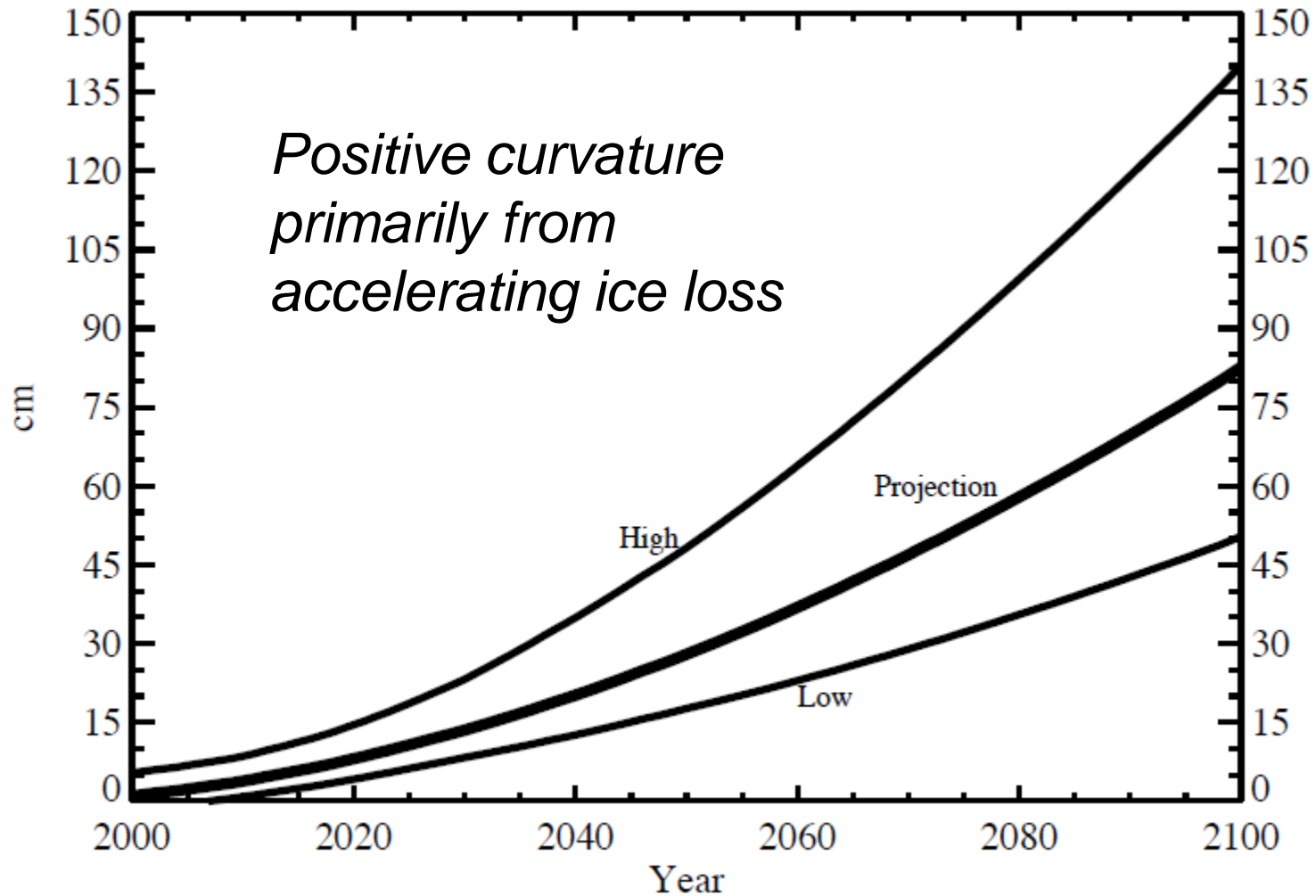
- **Climate models (IPCC)**
 - Based on knowledge of physical processes
 - Underestimated land ice contribution
- **Land ice extrapolations**
 - Based on observed trends in recent ice losses
 - Reliable for a few to several decades
- **Semi-empirical methods (Vermeer & Rahmstorf)**
 - Based on the observation that sea level rises faster as the Earth gets warmer
 - Highest projections require unrealistic acceleration of glaciological processes

Committee Approach to Global Projections

Developed a projection and range for each component

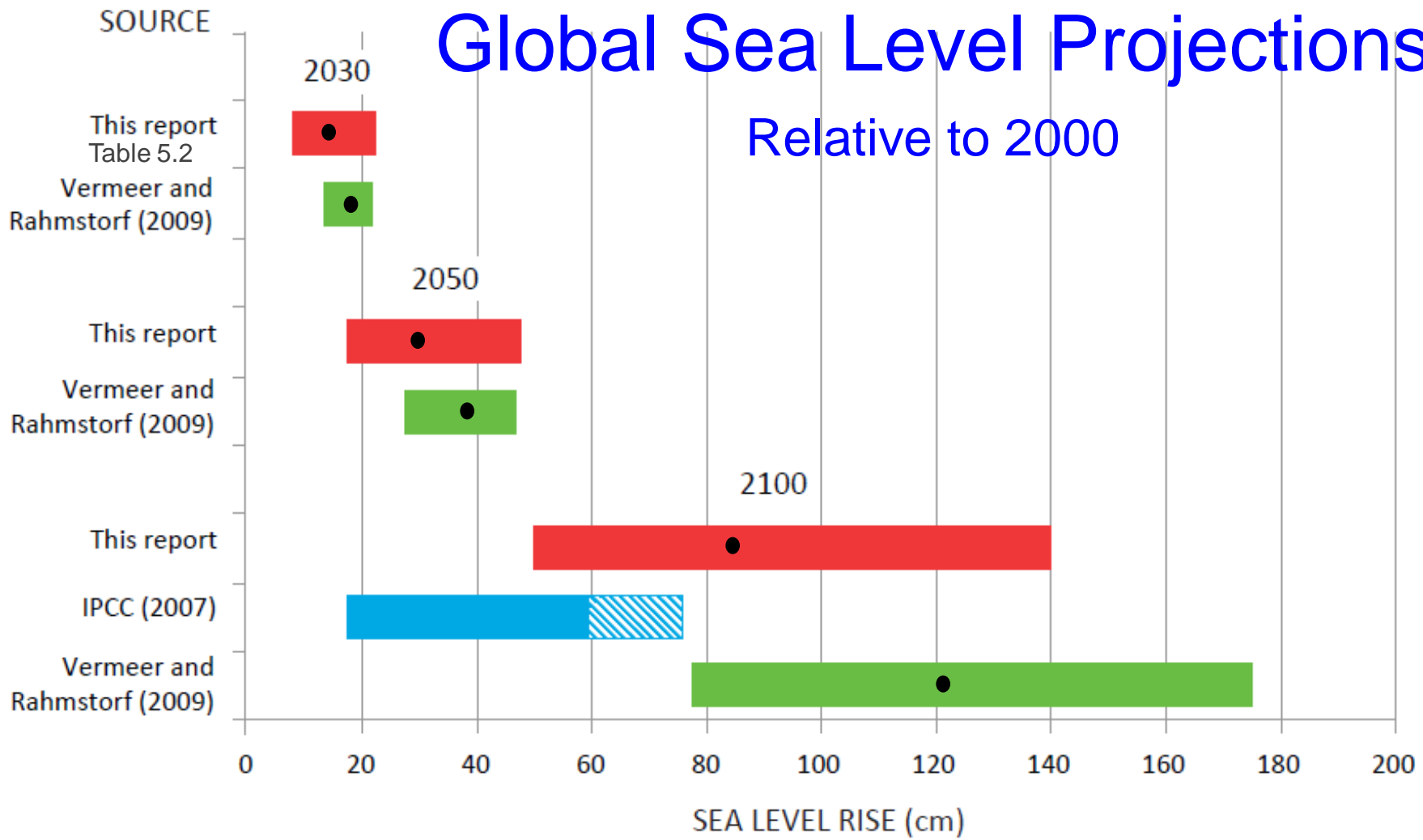
- Thermal expansion (steric) contribution determined from IPCC (2007) global climate models
 - Range due to different greenhouse gas scenarios
- Cryosphere contribution extrapolated from 1992-2010 trends in observed ice loss
 - Range includes added rapid dynamic response
- Land hydrology contribution too small and uncertain to be projected

Committee's Global Projections



Global Sea Level Projections

Relative to 2000



Committee projections for 2100 are higher than IPCC (2007) and lower than Vermeer and Rahmstorf (2009)

Task 2: Sea-Level Rise in California, Oregon, and Washington

- Estimate regional and local contributions to sea-level rise along the U.S. west coast
- Project sea-level rise along the coasts of California, Oregon, and Washington for 2030, 2050, and 2100

Factors that Affect Sea-Level Rise Along the U.S. West Coast

- Global sea-level rise
- Atmosphere-ocean circulation patterns in the northeast Pacific, which affect ocean levels
- Melting of modern and Ice Age glaciers and ice sheets, which affect ocean and land levels
- Tectonics and fluid withdrawal/recharge, which affect land levels

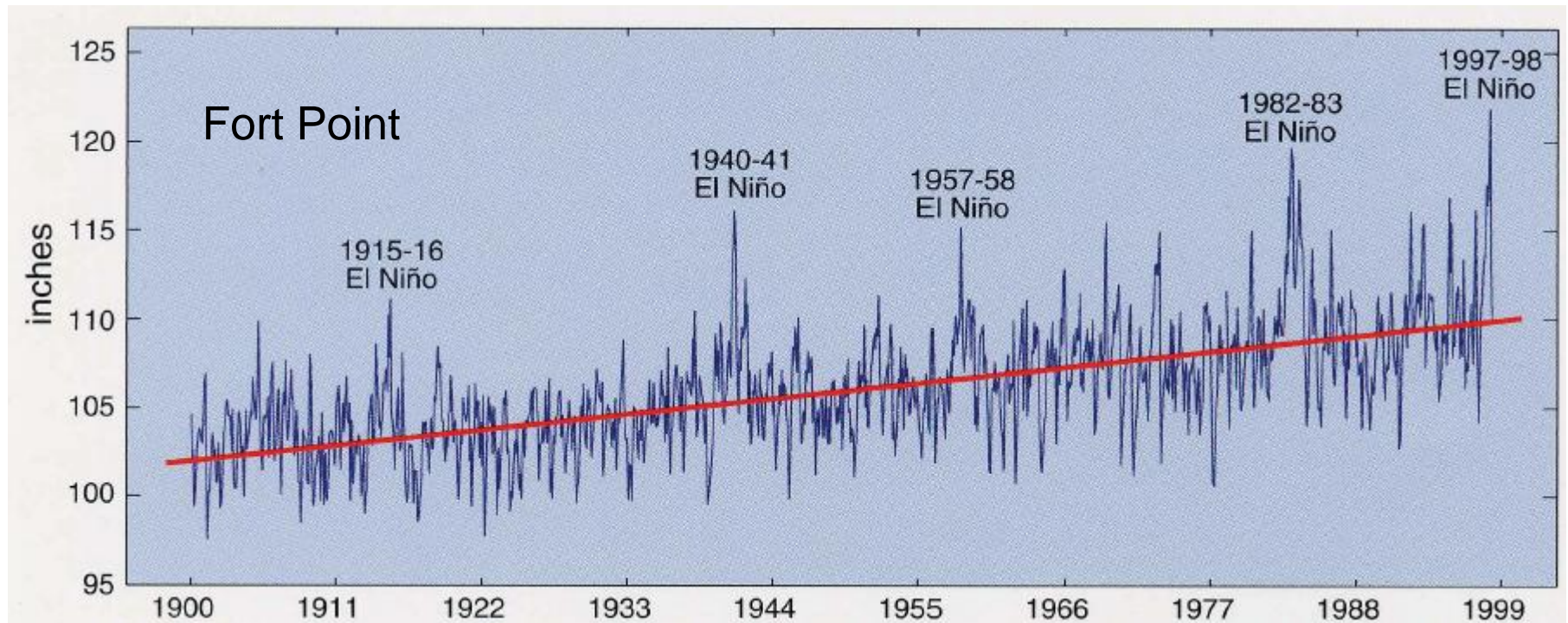
Local sea level rises if the ocean rises and/or the land sinks

Sea-Level Fingerprint of Land Ice Melt

- Melting of glaciers and ice sheets leaves a fingerprint on sea level
 - The large mass of the ice 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
- Melting of nearby (Alaska) and large (Greenland) ice masses reduces the rise in sea level, especially in northern Washington, while melting of Antarctica increases the rise in sea level

Ocean-Atmosphere Circulation Patterns

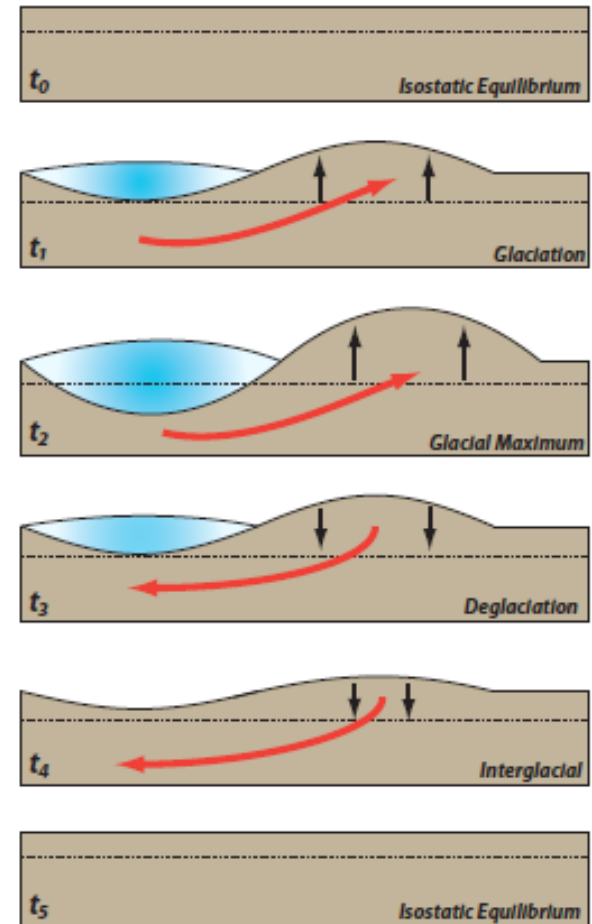
Local sea level rises during warm climate phases like El Niño, and falls during cool climate phases like La Niña



Glacial Isostatic Adjustment

The continents continue to respond to the disappearance of North American ice sheets that began 20,000 years ago

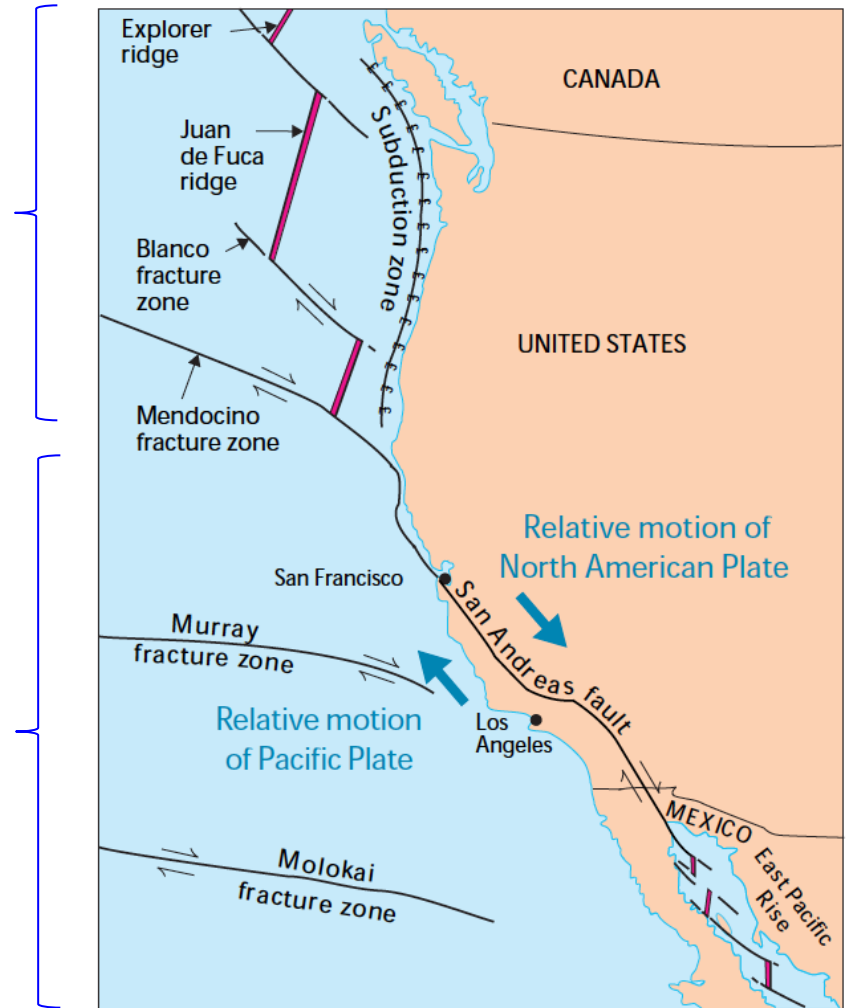
- Areas under the former ice sheet (northernmost Washington) are rising
- Areas at the margins of the ice sheet and beyond (the rest of Washington, Oregon, and California) are sinking



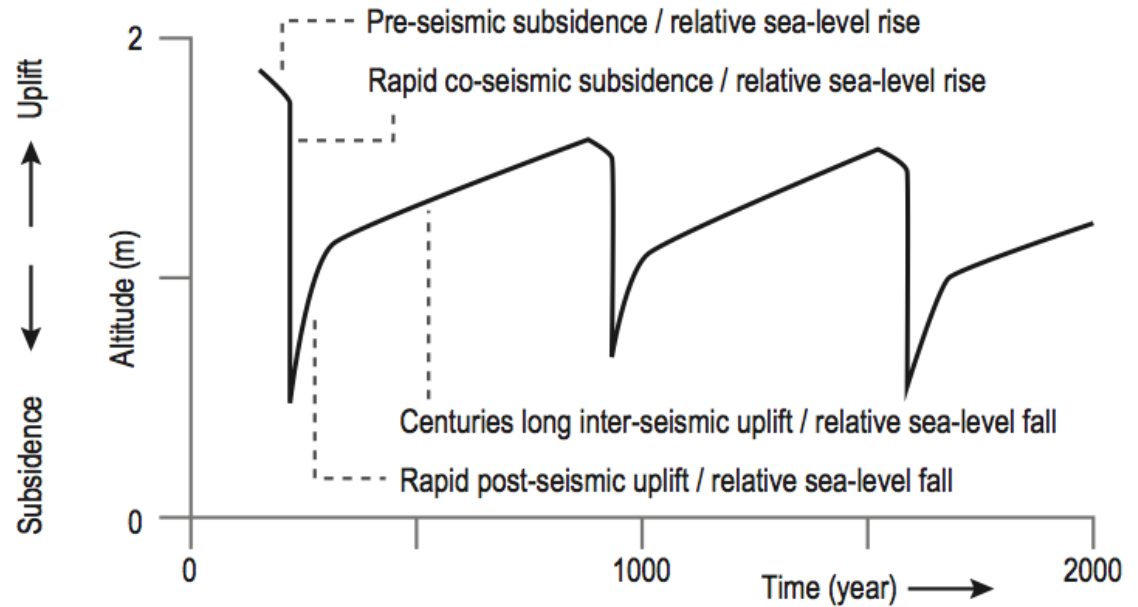
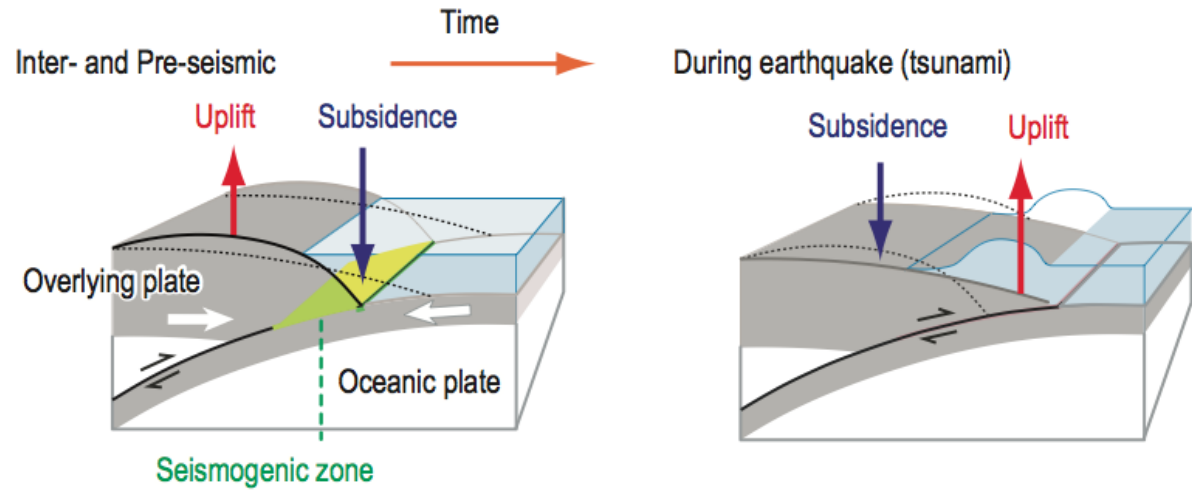
Tectonics

The ocean plate is descending below North America at the Cascadia Subduction Zone, causing local coastal areas to rise

Ocean and North America plates are sliding past one another along the San Andreas Fault, causing no vertical motion



Subduction Zone Uplift and Subsidence

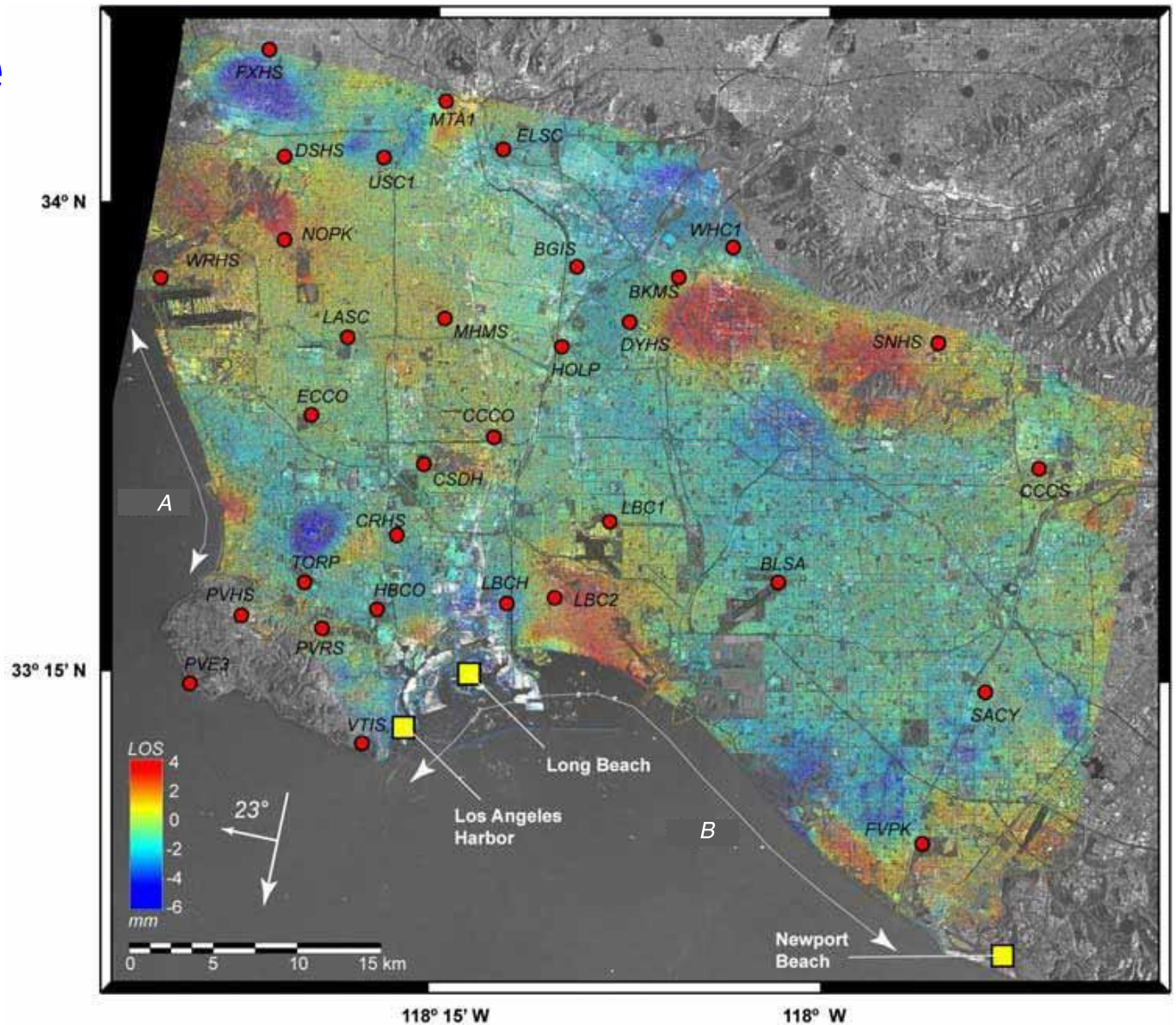


Fluid Withdrawal and Sediment Compaction

- Groundwater or hydrocarbon extraction can cause significant subsidence if fluids are not returned to the subsurface
- Peat- and mud-rich estuaries and tidal marshes may subside as a result of compaction
- These effects are too local to affect the regional projections

Variable Vertical Land Motion near LA

1992-2000
CGPS and InSAR
(in mm)



Committee Approach to Projections for California, Oregon, and Washington

- Northeast Pacific Ocean steric and wind-driven component was obtained from global climate models
- Global cryosphere component was adjusted for sea-level fingerprint effects, then extrapolated forward
- Vertical land motions were extrapolated from trends in GPS coastal observations

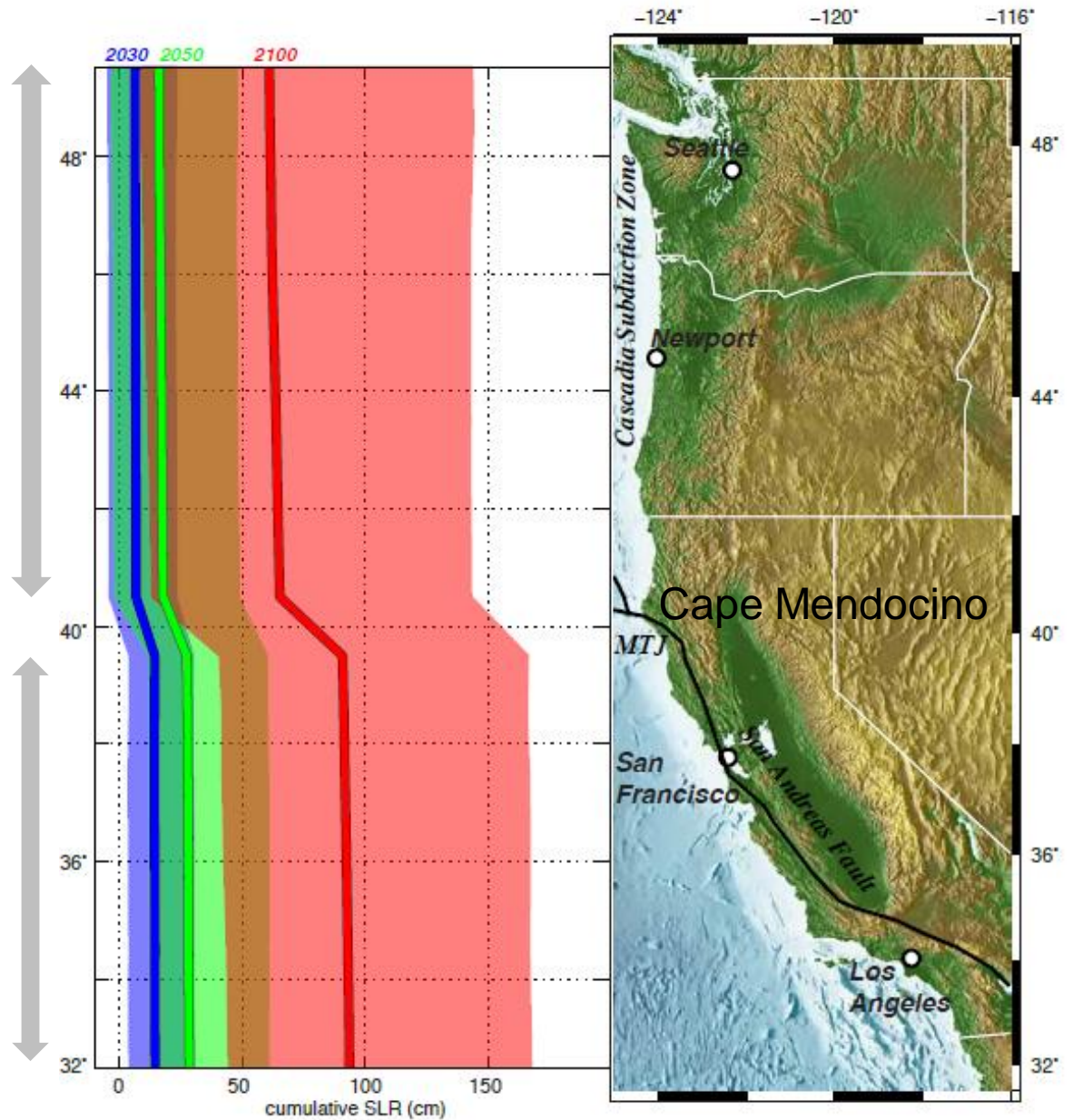
Regional averages were determined for areas to the north and to the south of Cape Mendocino

Committee's West Coast Projections

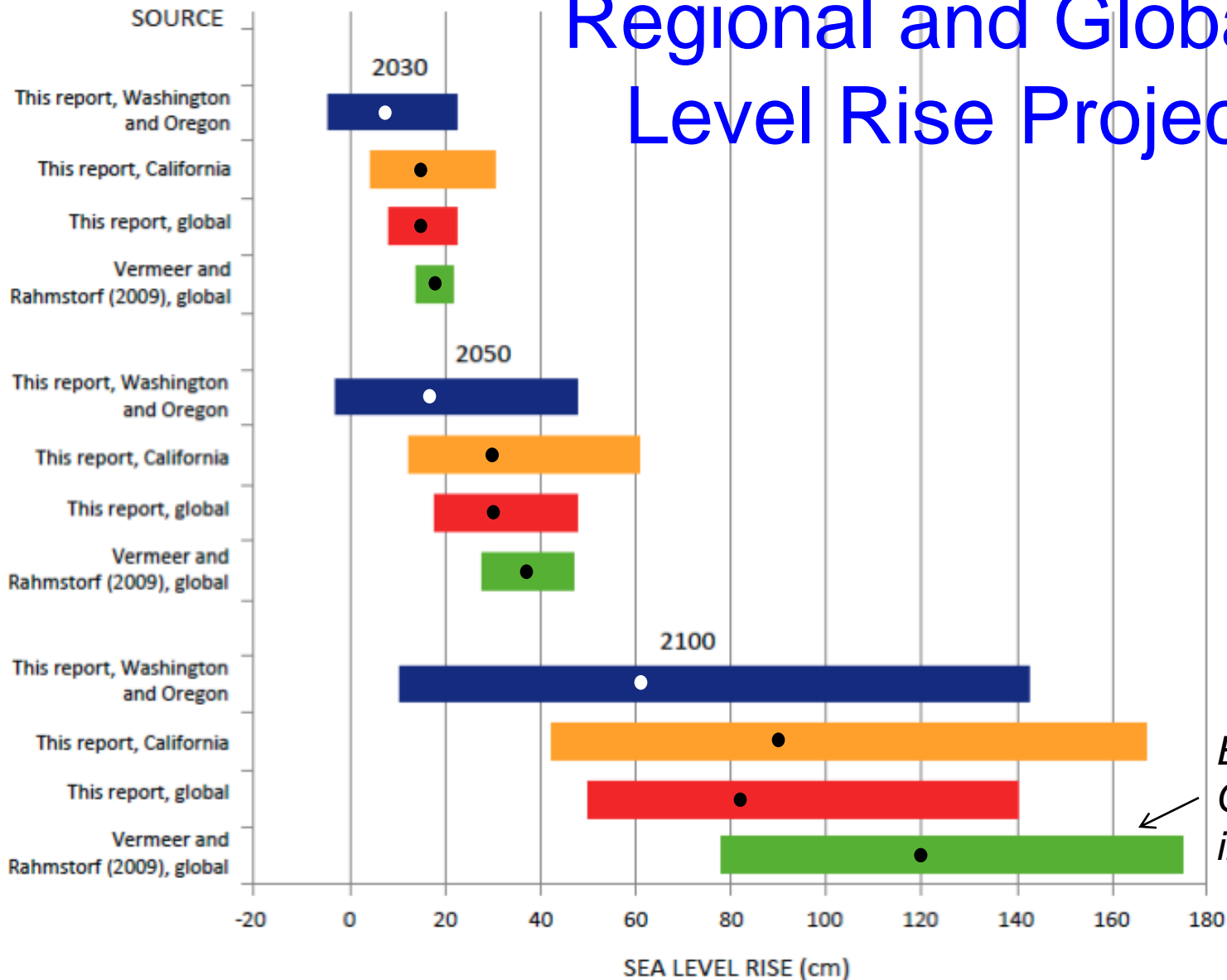
Land uplift + fingerprinting

Land subsidence

Blue: 2030
Green: 2050
Red: 2100



Regional and Global Sea-Level Rise Projections



Being used by California for interim planning

Sea Level Projections and Ranges (cm) for West Coast Cities

City	2030	2050	2100
Seattle	7 (-4 to 23)	17 (-3 to 48)	62 (10 to 143)
Newport	7 (-4 to 23)	17 (-2 to 48)	63 (12 to 142)
San Francisco	14 (4 to 30)	28 (12 to 61)	92 (42 to 166)
Los Angeles	15 (5 to 30)	28 (13 to 61)	93 (44 to 167)

Large north-south difference reflects the change in tectonics

Slight gradient reflects the sea-level fingerprint, which lowers projections, in decreasing amounts, from north to south

Uncertainty

- Regional projections are more uncertain than global projections because there are more components
- Uncertainties grow as the projection period lengthens
 - Incomplete understanding of the climate system
 - Difficulty of modeling all components
 - Shortage of data at appropriate scales
 - Need for assumptions about future conditions
- Confidence in the projections
 - High for 2030 and perhaps 2050
 - By 2100, we are confident only that the value will fall within the uncertainty bounds

Conclusions: Tasks 1 and 2

- Sea level along the California coast south of Cape Mendocino is expected to rise nearly 1 m by 2100, about the same as global sea-level rise
- The projected rise is lower in Washington, Oregon, and California north of Cape Mendocino, about 60 cm, because the land is rising as seismic strain builds up

A great earthquake (magnitude 8 or larger) along the Cascadia Subduction Zone would cause immediate subsidence and sea-level rise of an additional 1-2 m

Task 2a. Changes in Storminess

Summarize what is known about:

- Climate-induced increases in storm frequency and magnitude
- Related changes to sea-level rise projections

Catastrophic Coastal Storms

- Most coastal damage is caused by the confluence of large waves, storm surges, and high astronomical tides during a strong El Niño

Such an event in 1982-83 caused more than \$200 M in damage to California

- Water levels during these events can exceed projections for 2100
Their additive effects are significant



Model Predictions of Storminess

- No consensus among climate models whether the number and severity of storms in the northeast Pacific will change
- Some models predict that the North Pacific storm tracks will move north
 - If so, the impact of winter storms would decrease in southern California, and possibly increase in Oregon and Washington
- Most observational records are not long enough to confirm whether storm tracks are shifting

Observations: High Waves and Winds

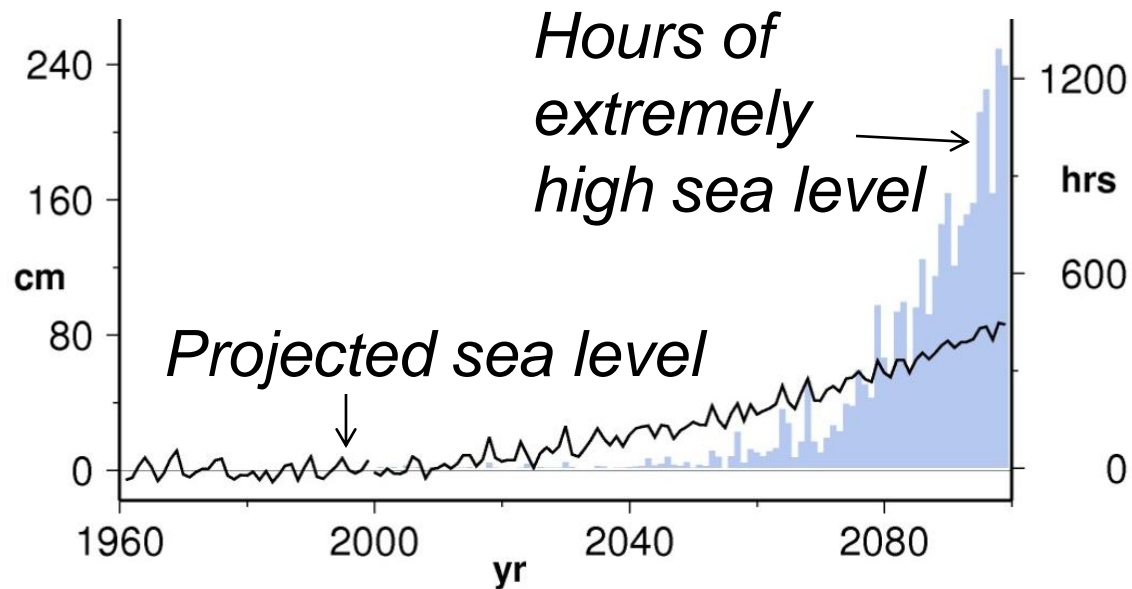
- Some observational studies report that the largest waves are getting higher and that winds are getting stronger

If so, the frequency and magnitude of extremely high coastal wave events will likely increase



- Records are too short (35 years) to determine the extent to which these changes reflect a long-term trend vs. natural climate variability

Sea-level rise will magnify the adverse impact of storm surges and high waves on the coast



Extreme high sea level events (>1.4 m above historical mean sea level) in San Francisco Bay is projected to increase substantially with sea-level rise based on model results

Tasks 2b and 2c. Shoreline Responses

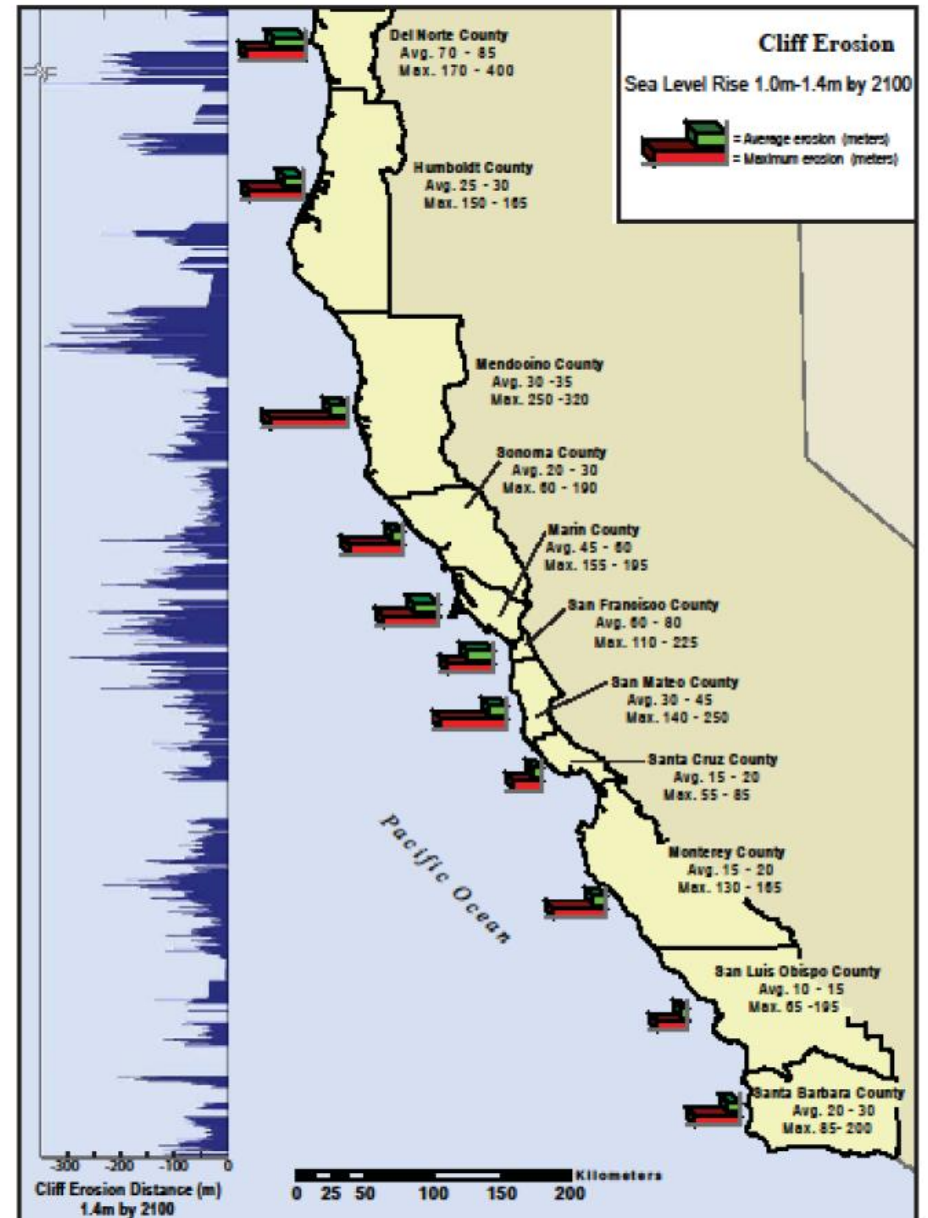
Summarize what is known about:

- Response of coastal cliffs and bluffs, beaches and dunes, marshes and mudflats to future sea-level rise and storminess
- Role of these environments in protecting against future inundation and waves

Little research specific to west coast sea-level rise

Coastal Cliffs, Dunes, and Beaches

- Storms and sea-level rise are causing coastlines to retreat at rates from a few cm/yr to several m/yr
 - Sea-level rise and higher waves would increase rates
- Cliffs could retreat more than 30 m by 2100



Marshes and Mudflats

- Protect inland areas by reducing flooding and wave height and energy
- Extent depends on local factors
 - Vegetation roughness, stem height, and density
 - Coastal topography and bathymetry
- Little research on west coast species



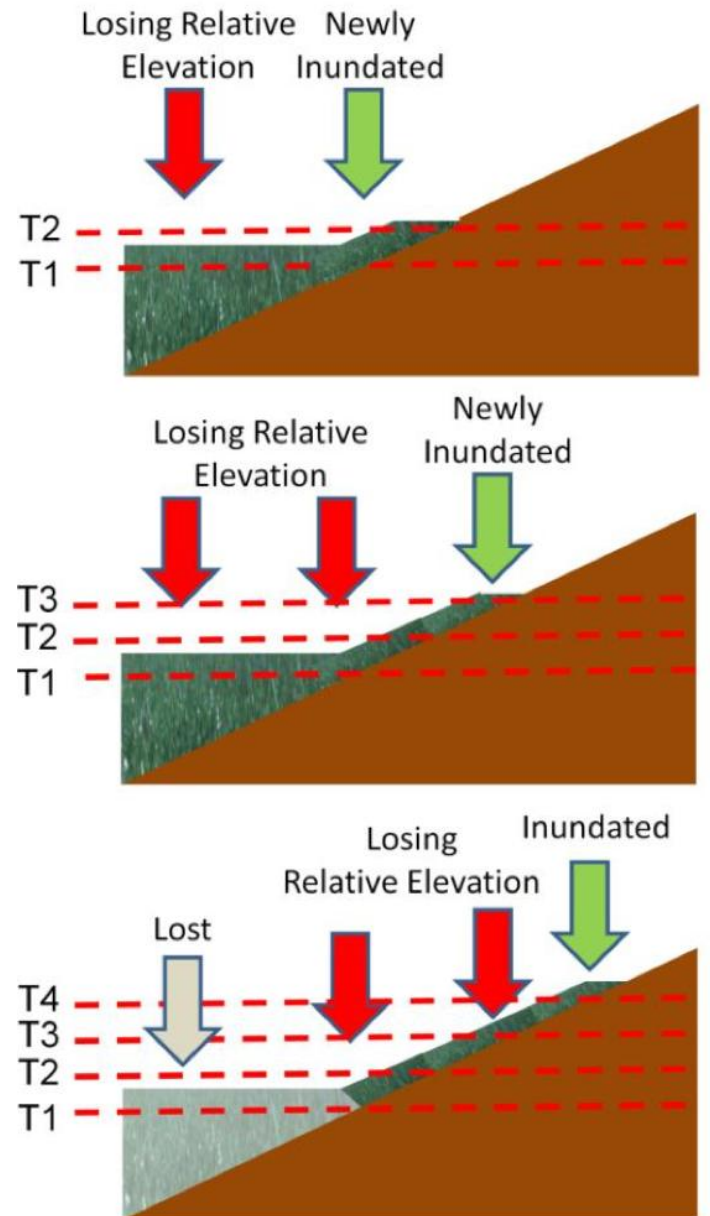
Wetlands Response to Sea-Level Rise

- Wetlands likely to keep pace with sea level until 2050
- Wetland survival until 2100 depends on maintaining elevation:

High rates of sedimentation and accumulation of organic matter

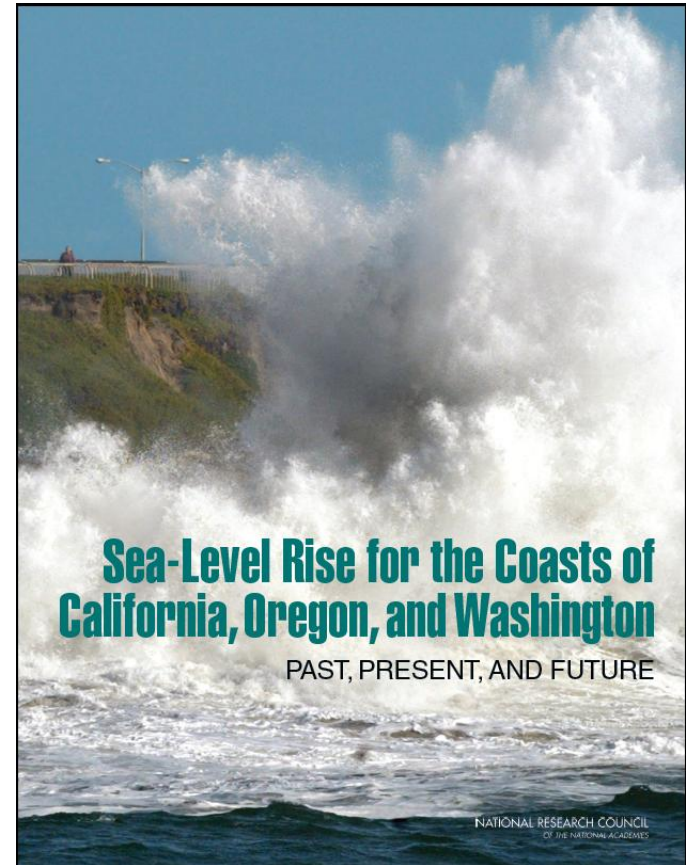
Accommodation area

Uplift



Next Steps

- June 21: Congressional briefings
- June 22, 3:00 pm eastern: Public release
- July 2: Report goes to NAP for layout and printing
- September: Glossy report distributed



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