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TO: Commissioners and Alternates

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SUBJECT: Staff Report Summarizing *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future"* published by the National Research Council
(For Commission information only)

Summary

The State of California requested in 2008, that the National Research Council (NRC) assess sea-level rise estimates to inform state adaptation efforts. The states of Washington and Oregon, the U.S. Army Corps of Engineers, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey subsequently joined California in sponsoring this study to evaluate sea-level rise in the global oceans and along the coasts of California, Oregon, and Washington for 2030, 2050, and 2100. The following summarizes the key findings from that report, particularly information relevant to San Francisco Bay. Most of the material below is excerpted from a summary of the report prepared by the National Research Council Committee.

Staff Report

Background. Sea level rose during the 20th century, and observations and projections suggest that it will rise at a higher rate during the 21st century. Rising seas increase the risk of coastal flooding, storm surge inundation, coastal erosion and shoreline retreat, and wetland loss. The cities and infrastructure that line many coasts are already vulnerable to damage from storms, which is likely to increase as sea level continues to rise and inundate areas further inland.

Global mean sea level is rising primarily because global temperatures are rising, causing ocean water to expand and land ice to melt. However, sea-level rise is not uniform; it varies from place to place. Sea-level rise along the coasts of California, Oregon, and Washington (referred to hereafter as the U.S. west coast) depends on the global mean sea-level rise and also on regional factors, such as ocean and atmospheric circulation patterns in the northern Pacific Ocean, the gravitational and deformational effects of land ice mass changes, and tectonics along the coast.

The comparative importance of these factors determines whether local sea level is higher or lower than the global mean, and how fast it is changing. Such information has enormous implications for coastal planning. California Executive Order S-13-08 directed state agencies to plan for sea-level rise and coastal impacts, and it also requested the National Research Council

(NRC) to establish a committee to assess sea-level rise to inform these state efforts. The states of Washington and Oregon, the U.S. Army Corps of Engineers, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey subsequently joined California in sponsoring this study to evaluate sea-level rise in the global oceans and along the coasts of California, Oregon, and Washington for 2030, 2050, and 2100.

The NRC Committee's (Committee) new projections for sea level rise take into account melting land ice, subsidence and uplift that affect relative sea level rise, thermal expansion of ocean waters due to increasing temperatures, and oceanographic forces, such as El Niño's and the Pacific Decadal Oscillation and the gravitational pull of land ice. The following text includes verbatim excerpts from the Committee's report. The pre-publication report can be downloaded at http://www.nap.edu/catalog.php?record_id=13389.

Components of Global Sea Level Rise. A warming climate causes global sea level to rise 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. Human activities that transfer water between the land and ocean also affect global sea level change. In particular, water withdrawn from aquifers eventually reaches the ocean, raising global sea level, whereas water stored behind dams effectively lowers global sea level.

The IPCC in 2007 placed greater emphasis on the contribution of thermal expansion to global sea level rise, in comparison to more recent findings. New research results indicate that the relative contribution of land ice to global sea level rise is increasing. Since 2006, the ice loss rate from the Greenland Ice Sheet has increased, and, according to most analyses, the contribution of Antarctic ice 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.

As a result of higher observed ice loss rates and a lower (corrected) contribution from thermal expansion, land ice is currently the largest contributor to global sea level rise. In the most recent published estimate, land ice accounted for about 65 percent of the total sea level rise from 1993 to 2008. The contributions of groundwater withdrawal and reservoir storage to sea-level change remain poorly understood, largely due to sparse data and inadequate models. Each process likely has a significant but opposite effect on sea-level change, on the order of 0.5 mm per year.

Global Projections. The Committee chose a combination of approaches for its projections. The Committee projected the steric[1] component of sea-level rise using output from global ocean models under an IPCC (2007) mid-range greenhouse gas emission scenario. The land ice component was extrapolated using the best available compilations of ice mass accumulation and loss (mass balance), which extend from 1960 to 2005 for glaciers and ice caps, and from 1992 to 2010 for the Greenland and Antarctic ice sheets. The contributions were then summed. The committee did not project the land hydrology contribution because available estimates suggested that the sum of groundwater extraction and reservoir storage is near zero, within large uncertainties.

Based on these calculations, the Committee estimates that global sea level will rise 8–23 cm (3.2 – 9 inches) by 2030 relative to 2000, 18–48 cm (7–18.9 inches) by 2050, and 50–140 cm (19.7–55 inches) by 2100. The ranges reflect uncertainties related to the fit of the data; the level of future greenhouse emissions, which affects the steric component; and any future changes in the rate of ice flow, which affects the total ice contribution. These uncertainties, and hence the ranges, grow with the length of the projection period.

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[1] Sea level rises and falls as the temperature and salinity of the water column varies, which is known as steric sea level. (NASA 2011)

The Committee's global projections for 2030 and 2050 are similar to the Vermeer and Rahmstorf (2009) projections for the same periods, but they have a wider range. For 2100, the committee's projection is substantially higher than IPCC's projection (18–59 cm with an additional 17 cm if rapid dynamical changes in ice flow are included), mainly because of a faster growing land ice component, and lower than Vermeer and Rahmstorf's projection (78–175 cm).

Projections for California, Oregon, and Washington

Sea-level rise off the west coast of the United States is influenced by a variety of local factors; therefore, sea-level projections for California, Oregon, and Washington differ from global projections. The factors that affect local sea-level projections include steric variations; wind-driven differences in ocean heights; gravitational and deformational effects (sea-level fingerprints) of melting of ice from Alaska, Greenland, and Antarctica; and vertical land motions along the coast. The local steric and wind-driven components were estimated by extracting northeast Pacific data from the same ocean models used for the global projections. The land ice component was adjusted for gravitational and deformational effects and then extrapolated forward. Finally, vertical land motion was projected using continuous GPS measurements for two tectonically distinct areas: Cascadia, where the coastline is generally rising, and the San Andreas region, where the coastline is generally subsiding.

TABLE 5.3 Regional Sea-Level Rise Projections (in cm) Relative to Year 2000

	2030		2050		2100	
Component	Projection	Range	Projection	Range	Projection	Range
Steric and dynamic ocean[a]	3.6 ± 2.5	0.0–9.3 (B1–A1FI)	7.8 ± 3.7	2.2–16.1 (B1–A1FI)	20.9 ± 7.7	9.9–37.1 (B1–A1FI)
Non-Alaska glaciers and ice caps[b]	2.4 ± 0.2		4.4 ± 0.3		11.4 ± 1.0	
Alaska, Greenland, and Antarctica with sea-level fingerprint effect[c]						
Seattle, WA	7.1	5.4–9.5	16.0	11.1–22.1	52.7	32.7–74.9
Newport, OR	7.4	5.6–9.5	16.6	11.7–22.2	54.5	34.1–75.3
San Francisco, CA	7.8	6.1–9.6	17.6	12.7–22.3	57.6	37.3–76.1
Los Angeles, CA	8.0	6.3–9.6	17.9	13.0–22.3	58.5	38.6–76.4
Vertical land motion[d]						
North of Cape Mendocino	-3.0	-7.5–1.5	-5.0	-12.5–2.5	-10.0	-25.0–5.0
South of Cape Mendocino	4.5	0.6–8.4	7.5	1.0–14.0	15.0	2.0–28.0
Sum of all contributions						
Seattle	6.6 ± 5.6	-3.7–22.5	16.6 ± 10.5	-2.5–47.8	61.8 ± 29.3	10.0–143.0
Newport	6.8 ± 5.6	-3.5–22.7	17.2 ± 10.3	-2.1–48.1	63.3 ± 28.3	11.7–142.4
San Francisco	14.4 ± 5.0	4.3–29.7	28.0 ± 9.2	12.3–60.8	91.9 ± 25.5	42.4–166.4
Los Angeles	14.7 ± 5.0	4.6–30.0	28.4 ± 9.0	12.7–60.8	93.1 ± 24.9	44.2–166.5

[a] Projection indicates the mean and ± standard deviation computed for the Pacific coast from the gridded data presented in Pardaens et al. (2010) for the A1B scenario. Ranges are the means for B1 and A1FI using the scaling in Table 10.7 of IPCC (2007; see also Table 5.1 of this report): (B1/A1B) = (0.1/0.13); (A1FI/A1B) = (0.17/0.13).

[b] Extrapolated based on ice loss rates for glaciers and ice caps except Alaska, Greenland, and Antarctica. No ranges are given because these sources are assumed to have a small or uniform effect on the gradient in sea-level change along the U.S. west coast (see "Sea-Level Fingerprints of Modern Land Ice Change" in Chapter 4).

[c] Extrapolation based on ice loss rates and gravitational attraction effects for Alaska, Greenland, and Antarctica. Ranges reflect uncertainty in ice loss rates.

[d] Assumes constant rates of vertical land motion of 1.0 ± 1.5 mm yr^{-1} for Cascadia and -1.5 ± 1.3 mm yr^{-1} for the San Andreas region. The signs were reversed to calculate relative sea level. Uncertainties are 1 standard deviation.

For the California coast south of Cape Mendocino, the committee projects that sea level will rise 4–30 cm (1.6-11.8 inches) by 2030 relative to 2000, 12–61 cm (4.7-24 inches) by 2050, and 42–167 cm (16.5-65.7 inches) by 2100. The committee's projections for the California coast are slightly higher than its global projections, primarily because much of the coastline is subsiding. The California projections are somewhat lower, but have wider ranges than the Vermeer and Rahmstorf (2009) global projections, which are being used by California on an interim basis for coastal planning. California's Ocean Protection Council (OPC) issued interim sea level rise guidance in 2010 developed by the Sea Level Rise Task Force of the Coastal and Ocean Working Group of the California Climate Action Team (COCAT) with science support provided by the OPC's Science Advisory Team and the California Ocean Science Trust (Table 1).

Table 1. Sea-Level Rise Projections using 2000 as the Baseline

Year		Average of Models	Range of Models
2030		7 in (18 cm)	5-8 in (13-21 cm)
2050		14 in (36 cm)	10-17 in (26-43 cm)
2070	Low	23 in (59 cm)	17-27 in (43-70 cm)
	Medium	24 in (62 cm)	18-29 in (46-74 cm)
	High	27 in (69 cm)	20-32 in (51-81 cm)
2100	Low	40 in (101 cm)	31-50 in (78-128 cm)
	Medium	47 in (121 cm)	37-60 in (95-152 cm)
	High	55 in (140 cm)	43-69 in (110-176 cm)

The Commission has used a mid-century sea level rise projection of 16 inches, and an end of century projection of 55 inches in both its regional vulnerability assessment entitled *Living with a Rising Bay*, and in the Adapting to Rising Tides project, being conducted in partnership with local governments and special districts in Alameda County. These values are consistent with the interim guidance provided by the COCAT, and with the more recent projections from the NRC, albeit at the more conservative end of those projections.

The projections of future sea-level rise have large uncertainties resulting from an incomplete understanding of the global climate system, the inability of global climate models to accurately represent all important components of the climate system at global or regional scales, a shortage of data at the temporal and spatial scales necessary to constrain the models, and the need to make assumptions about future conditions (e.g., greenhouse gas emissions, large volcanic eruptions) that drive the climate system. As the projection period lengthens, uncertainty in the projections grows. At short timescales (2030 and perhaps 2050), when the models more closely represent the future climate system, confidence in the global and regional projections is relatively high. By 2100, however, projections made using process-based numerical models, extrapolations, and semi-empirical methods all have large uncertainties. The actual sea-level rise will almost surely fall somewhere within the wide uncertainty bounds, 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 astronomical tides during a strong El Niño. The water levels reached during these large, short-term events have exceeded mean sea levels projected for 2100, so understanding their additive effects is crucial for coastal planning.

Changes in Storm Frequency and Magnitude. Climate change has been postulated to induce changes in storm frequency, magnitude, and direction. To date, there is no consensus among climate model simulations about whether the number and severity of storms will change in the northeast Pacific. A number of climate models predict a northward shift in the North Pacific storm track over the course of the 21st century, which could lessen the impact of winter storms in southern California and possibly increase their impact in Oregon and Washington. However, these changes may not emerge for a few decades, and most observational records are not yet long enough to determine conclusively whether storm tracks are moving north.

Several observational studies have reported that the largest waves have been getting higher and that winds have been getting stronger in the northeastern Pacific over the past few decades. Interpretation of these trends is controversial because wave and wind records are short, extending back only about 35 years. At least part of the observed increase likely reflects natural climate variability of the Pacific atmosphere-ocean system, particularly the occurrence of large El Niños and inter-decadal fluctuations. If some or all of the increase represents a long-term trend, the frequency and magnitude of extremely high coastal wave events will likely increase.

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 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 to several thousand hours per decade by 2100.

Coastal Responses to Sea-Level Rise and Storminess. The natural shoreline can provide partial protection for coastal development against sea level rise and storms. Marshes and mudflats protect inland areas by storing flood waters and damping wave height and energy. To continue providing these services as sea level rises, marshes must be able to maintain their elevation relative to sea level and to move inland in places where they are subject to erosion at the seaward edge. Building elevation requires a sufficient supply of sediment and accumulation of organic material. Most studies of west coast marshes have focused on the supply of sediment. 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 by the Committee. For 2100, marshes will need room to migrate, a high sediment supply, and uplift or low subsidence to survive the projected sea-level rise.