EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 93 NUMBER 27
3 JULY 2012
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Understanding North Pacific Sea Level Trends

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Rising sea level poses significant challenges to infrastructure and populations, particularly for coastal [*Heberger et al.*, 2009] and island communities [*Webb and Kench*, 2010] in the North Pacific where population density at or near coastal waters is high. A significant portion of the United States' security, commerce, and ecosystem assets are located at or near the coast, making them vulnerable to sea level rise. Although global mean sea level (MSL) rise is a fundamental consideration, regional mean sea level (RSL) height variability within ocean basins and along their boundaries can be more critical, particularly in the North Pacific where the amplitude of interannual variability is high.

Causes of Global and Regional Sea Level Rise

The main causes for global MSL rise (Figure 1) are added water from the melting of ice sheets and glaciers and thermal expansion of the oceans [*Domingues et al.*, 2008], both driven by global warming [*Bindoff et al.*, 2007]. Regional sea level variations appear to fluctuate about the globally averaged trend, which has increased from the tide gauge estimate of about 1.7 ± 0.5 millimeters per year over the twentieth century [*Bindoff et al.*, 2007] to the satellite altimetry estimate of about 3.1 ± 0.7 millimeters per year since 1993 [e.g., *Bromirski et al.*, 2011; *Timmermann et al.*, 2010]. However, recent studies show that regional sea level trends are affected by local and remote wind forcing (Figure 1), which can cause sustained changes in ocean circulation and sea level height [*Bromirski et al.*, 2011; *Merrifield*, 2011; *Sturges and Douglas*, 2011; *Timmermann et al.*, 2010]. These studies cover different regions, indicating that RSL along most oceanic boundaries can be strongly affected by dynamic effects for sustained periods.

Along the U.S. Pacific coast, tide gauges suggest that regional sea level rise is approximately equal to global MSL rise over most of the twentieth century, but altimetry and tide gauges both indicate that RSL rise is significantly less than global MSL rise since about 1980 [*Bromirski et al.*, 2011; *Merrifield*, 2011; *Houston and Dean*, 2011]. In contrast, in the western tropical Pacific, RSL rise is much greater than global MSL rise since the early 1990s [*Merrifield*, 2011; *Bromirski et al.*, 2011]. Wind stress curl–related Ekman pumping and alongshore wind stress–related Ekman transport (Figure 1) mainly drive these regional departures from the global trend. These processes alter the thermocline depth, with a deeper thermocline associated with raised sea level height.

West Coast Sea Level Trends

Persistent regional wind stress patterns spanning a few decades [*Bromirski et al.*, 2011], as well as basin-wide wind-driven circulation changes and strong El Niño–related fluctuations on shorter time scales, strongly affect sea level trends along the Pacific coast of North America, exemplified by the San Francisco record (Figure 2). The recent U.S. West Coast "RSL less than MSL" rise rates are attributed to a dramatic change in eastern boundary and basin-wide wind stress patterns that occurred after the mid-1970s climate regime shift [*Miller et al.*, 1994]. This change in wind stress patterns has suppressed regional sea level rise along the West Coast, both in an absolute sense as well as relative to what is expected during a warm phase of the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997]. Similar near-zero RSL trends since 1980 are also observed at San Diego and Seattle [*Bromirski et al.*, 2011], which is consistent with altimetry observations. A similar protracted stationary West Coast RSL epoch occurred from about 1880 to 1930 (Figure 2), potentially also related to North Pacific wind stress patterns. Persistent wind stress regimes over the entire North Pacific basin have recently exhibited patterns and amplitudes not observed since before the mid-1970s regime shift, likely causing basin-scale thermocline adjustments. This change in broad-scale wind stress patterns may have foreshadowed a climate regime shift. The recent apparently-associated shift of PDO to its cold phase during the 2000s will further serve to suppress regional sea level rise along the West Coast if it persists.

In contrast to stationary eastern boundary sea levels, the strong regional sea level rise in the western tropical Pacific is related to a steady increase in the trade winds since the early 1990s [*Merrifield*, 2011]. Increasing trade winds are possibly associated with an intensification of the subtropical atmospheric Hadley circulation, which has been linked to an associated increase in midlatitude westerlies and equatorward winds along the Pacific coast of North America. The eastern boundary wind patterns that have contributed to the RSL less than MSL pattern along the West Coast [*Bromirski et al.*, 2011] may be associated with these Hadley circulation changes, although natural decadal variability associated with PDO and other climate modes makes this relationship statistically uncertain [*Merrifield*, 2011].

The near-zero regional sea level trend along the West Coast since about 1980 occurred following an apparent abrupt increase in RSL along the West Coast that occurred after the mid-1970s regime shift [*Bromirski et al.*, 2011], which is consistent with the change from the cold phase to the warm phase of PDO. A similar relatively abrupt increase in RSL, associated with a change in trend, may have occurred near 1930 (Figure 2), suggested by the difference between the 1880–1930 and 1930–1980 trend levels at 1930. It is interesting that the Cascais, Portugal, tide gauge record also shows a similar abrupt RSL increase near 1930 [*Sturges and Douglas*, 2011], potentially associated with changes in regional winds. The difference between pre-1930 and post-1980 mean RSL levels (red dashed lines in Figure 2) at San Francisco is about 15.8 centimeters, giving an RSL rise of about 3.2 millimeters per year over the 1930–1980 epoch, similar to recent altimetry global MSL rise estimates. Note that these epochs are somewhat arbitrary and that selection of other epoch boundaries would give slightly different results.

El Niño–Related Extremes

Although regional sea level along the West Coast is important for near-coastal

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processes and provides the base level upon which other shorter-term fluctuations are superimposed, El Niño–related extremes (e.g., during the 1940–1941, 1958–1959, 1982–1983, and 1997–1998 strong El Niños; Figure 2) produce high-amplitude interannual fluctuations at San Francisco that are comparable to the total global MSL rise over the entire twentieth century. These fluctuations are associated with poleward propagating coastally trapped waves and tropical teleconnections to the atmosphere that affect storm patterns across the basin.

The impacts of these fluctuations on flooding, beach erosion, and shoreline retreat will be amplified under rising coastal RSL because, particularly during high tides, increased water levels allow more wave energy to reach farther shoreward. Because ocean wave extremes and storm-forced nontide fluctuations are not expected to change appreciably over the 21st-century [*Bromirski et al.*, 2012], upward trends in regional sea level will be the dominant factor affecting the intensification of coastal erosion processes along the West Coast.

Sea Level Changes in the Future

Future regional sea level changes across the North Pacific will depend on the magnitude of changes in PDO and the trade wind mode, as well as other regional and basin-wide anomalies in wind forcing [*Bromirski et al.*, 2011; *Merrifield*, 2011]. RSL changes are also affected by vertical land movements both natural (e.g., glacial isostatic adjustments) and anthropogenic (e.g., subsidence associated with groundwater extraction), which can further complicate coastal RSL spatial patterns. While regional wind forcing is difficult to forecast on climate time scales, the recent apparent switch of PDO from its warm phase to its cold phase will likely cause substantial changes in North Pacific winds that will affect regional sea level trend patterns. Additionally, weakening and poleward expansion of Hadley cell circulation is anticipated under global warming [*Lu et al.*, 2007], with an associated poleward expansion of the subtropical dry zone. This could reduce trade wind strength and cause broad-scale ocean circulation changes that redistribute ocean water across the North Pacific basin and raise sea levels along the West Coast, although this regional effect is not statistically significant in previous ensemble mean model projections from the *Intergovernmental Panel on Climate Change* [2007, chapter 10.6.2].

The dynamics of the forcings that control Hadley cell intensity (and expansion and contraction) can couple with North Pacific decadal variability and with decadal oscillations of the tropical Pacific. If Hadley cell intensity is actually part of a decadal-scale oscillation associated with PDO, then West Coast sea level rise may also accelerate once the phase of the oscillation switches. The primary sea level signals from PDO-related climate variability are due to basin-scale "sloshing" of thermocline structure associated with wind stress (and its curl) forcing. Regional changes in sea level due to differences in surface heat flux forcing variability across the basin can also contribute to changes in regional sea level (Figure 1), but these effects appear to be much smaller than those due to wind stress changes [*Bromirski et al.*, 2011]. Understanding both regional-scale and gyre-scale responses of the North Pacific Ocean circulation to changes in the Hadley circulation is vital to anticipate the magnitude and timing of potential increases in RSL along the U.S. West Coast.

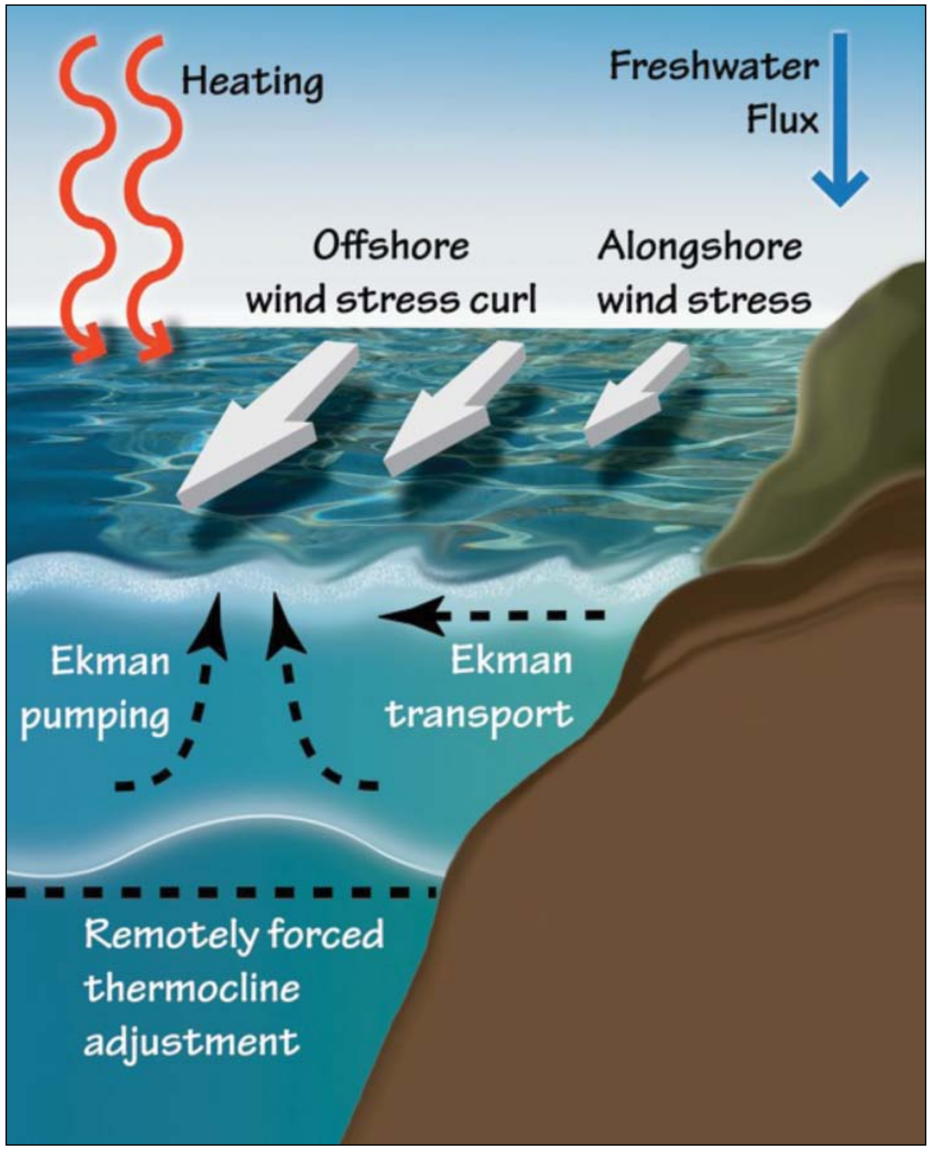

Fig. 1. Processes affecting sea levels along the eastern boundary of the North Pacific. Freshwater flux represents the net volume of added water from ice sheets, glaciers, runoff, precipitation, and evaporation, which contribute to global mean sea level. Heating represents the net effect of regional and global thermal forcing. Alongshore wind stress drives offshore Ekman transport that alters the thermocline depth, with associated changes in regional sea level. Ekman pumping offshore drives thermocline depth changes, both regionally and basin wide. Here upwelling is shown, raising the thermocline and thus lowering regional mean sea level (RSL). Downwelling produces the opposite effect on thermocline depth and RSL. Remotely forced thermocline adjustment results from basin-scale integrated effects of wind stress curl that are manifested in changes in broad-scale ocean circulation, also affecting RSL height.

Acknowledgments

We gratefully acknowledge support for this study from the California Department of Boating and Waterways contracts 11-106-107 and 10-106-106; from the National Oceanic and Atmospheric Administration through the Climate Change Data and Detection program grant NA10OAR4310121; from the U.S. National Science Foundation

(OCE-0960770); and from the California Energy Commission grant 500-09-038, sub-award CIEE POCV02-S02. Thanks to Linda Rasmussen for producing the schematic figure.

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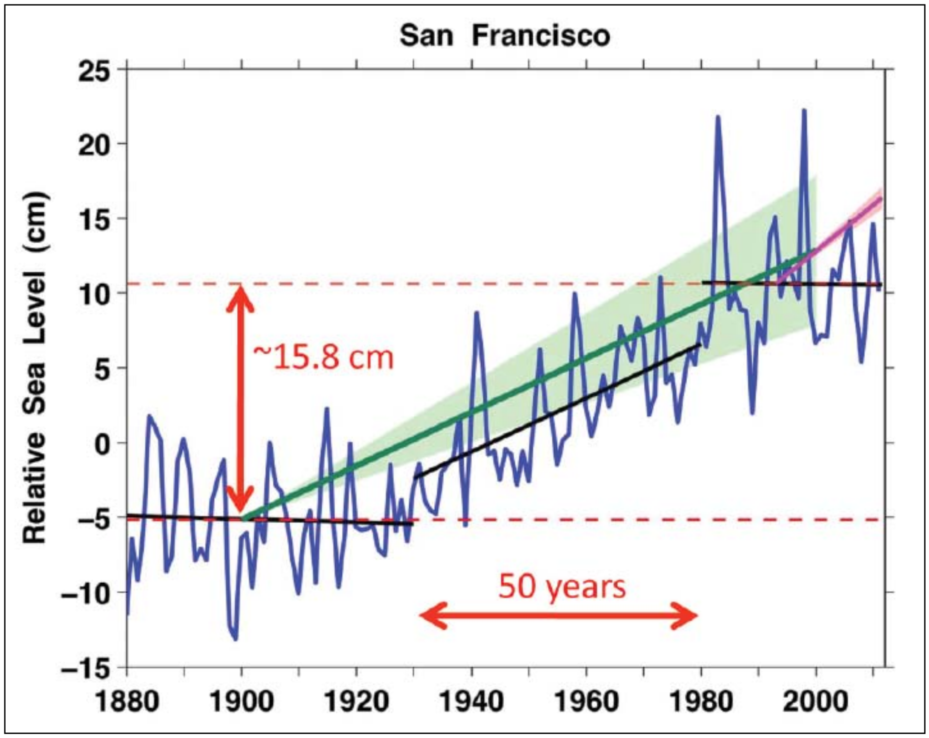

Fig. 2. The observed San Francisco tide gauge 3-year running mean sea levels (blue line). Trends in the tide gauge record (black lines) are near zero between 1880 and 1930 and since about 1980. The trend from 1930 to 1980 is close to the global mean sea level (MSL) rise rate (green line, green-shaded region denotes the 1.7 ± 0.5 millimeters per year bounds) [Bindoff et al., 2007]. Note that the global MSL satellite altimetry trend (magenta; 3.1 ± 0.7 millimeters per year) [Timmermann et al., 2010] is very different from the San Francisco regional sea level trend over the same period.

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