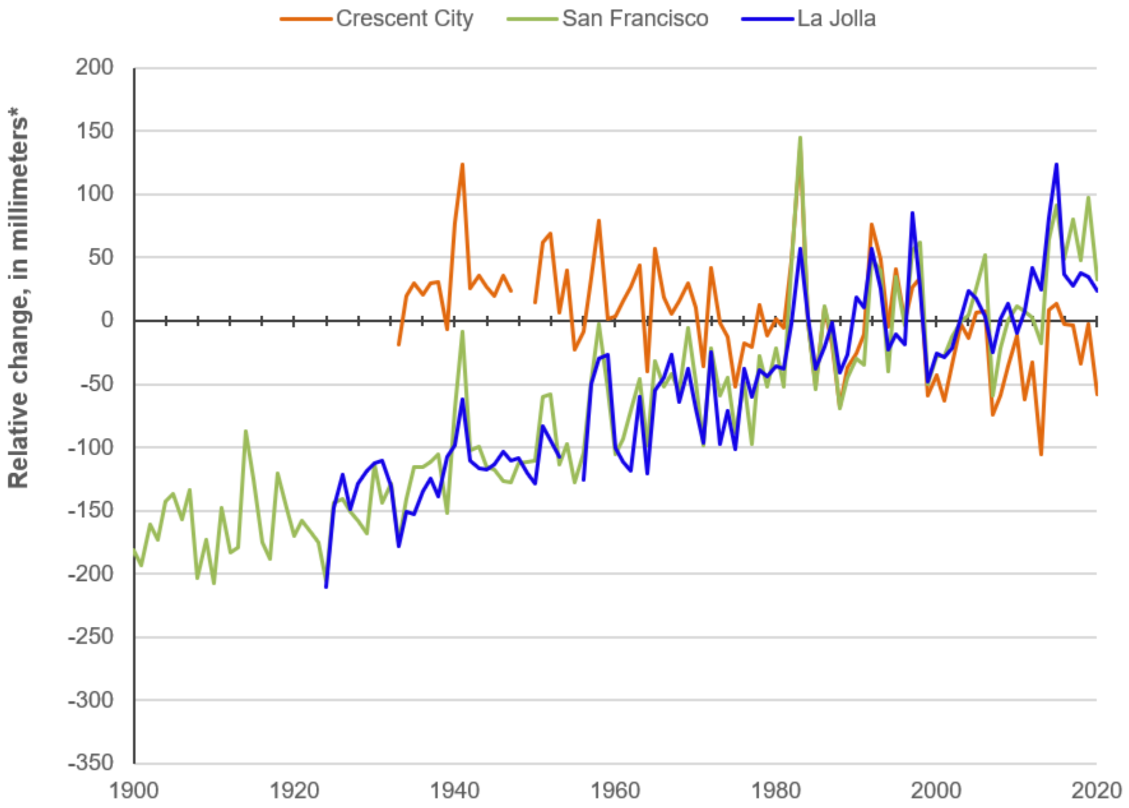
SEA LEVEL RISE

Sea levels along the California coast have risen over the past century, except along the far north coast where an uplift of the land surface has occurred due to the movement of the Earth's plates, resulting in a small relative fall in sea level.

Figure 1. Annual mean sea level trends



Source: NOAA, 2021a

**Relative to tidal datum (reference point set by NOAA)*

What does the indicator show?

As shown in Figure 1, mean sea levels have increased over the past century by about 200 millimeters (mm) (8 inches (″)) in San Francisco and in La Jolla. This is consistent across the California coastline except for Crescent City where the sea level has declined by about 80 mm (3″) due to regional land uplift driven by the movement of the Earth's plates. Sea level values are the average height of the ocean relative to the tidal datum, a standard elevation established by the National Oceanic and Atmospheric Administration (NOAA) as a reference point (see *Technical Considerations* for details).

Mean sea levels show year-to-year (interannual) variability. They peak during El Niño years (when the waters of the eastern Pacific Ocean became warmer, temporarily raising coastal water levels from 10 to 40 centimeters (cm), or about 4 to 16″). Levels at all three locations rose in 2014 and 2015, due to unusually warm sea surface temperatures in the Pacific Ocean during that period (Hu et al., 2017), further exacerbated by the large El Niño that peaked in late 2015 (Flick et al., 2016).

Trends at 17 tide stations in California (see map, Figure 2) are presented in Table 1, listed in order from north to south (NOAA, 2021).

Figure 2. Trends at California tide stations

Source: NOAA, 2021a

Interactive map is online at [NOAA's Tides and Currents webpage]()

Table 1. Sea Level Trends (stations listed from north to south)

Location	Period of record	Trend, mm/year (inches/year)
Crescent City	1933-2020	-0.79 (-0.03)
North Spit	1977-2020	+4.91 (+0.2)
Arena Cove	1978-2020	+0.89 (+0.04)
Port Chicago*	1976-2020	+2.03 (+0.08)
Point Reyes	1975-2020	+2.15 (+0.08)
Alameda*	1939-2020	+0.87 (+0.03)
San Francisco	1897-2020	+1.97 (+0.08)
Redwood City*	1974-2020	+2.54 (+0.1)
Monterey	1973-2020	+1.63 (+0.06)
Port San Luis	1945-2020	+0.96 (+0.04)
Santa Barbara	1973-2020	+1.08 (+0.04)
Rincon Island**	1962-1990	+3.22 (+0.1)
Santa Monica	1933-2020	+1.54 (+0.06)
Los Angeles	1923-2020	+1.03 (+0.04)
Newport Beach***	1955-1993	+2.22 (+0.09)
La Jolla	1924-2015	+2.13 (+0.08)
San Diego	1906-2020	+2.2 (+0.09)

** Gauge not along the outer coast*
*** Rincon Island is an artificial offshore island built for oil and gas production*
**** Inactive*

Source: NOAA, 2021a

The general trend towards higher sea levels in California is consistent with global observations (IPCC, 2021). Global sea-level rise is the most obvious manifestation of climate change in the ocean (Griggs et al., 2017). Global mean sea levels have been rising at increasing rates: by 1.3 mm/year between 1901 and 1971; 1.9 mm/year (about 0.07 inch/year) between 1971 and 2006; and 3.7 mm/ year (about 0.1 inch/year) between 2006 and 2018. Human influence on the climate was very likely the main driver of these increases since at least 1971 (IPCC, 2021).

Why is this indicator important?

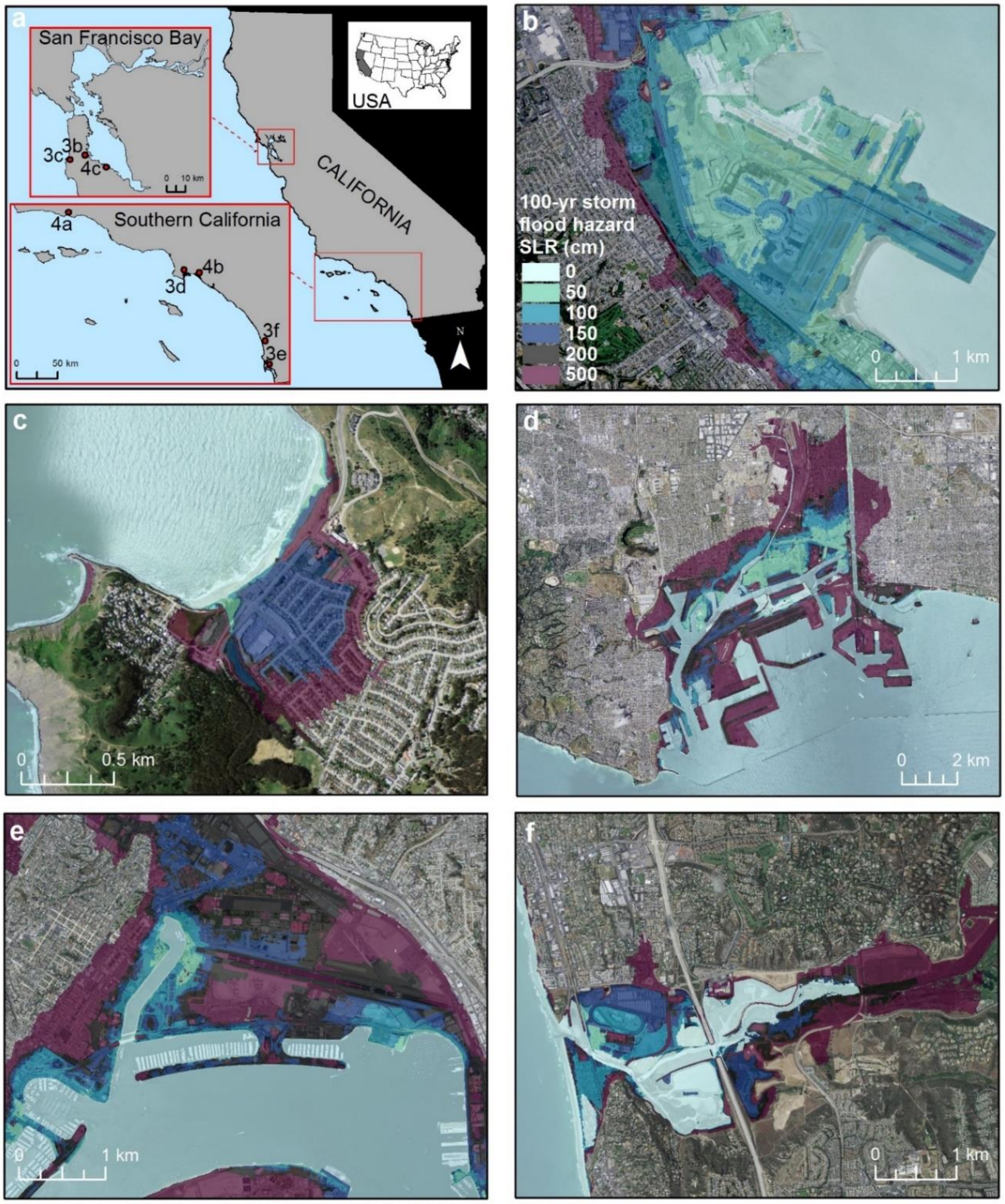
As sea level rise continues to accelerate throughout this century and beyond, coastal flooding, beach erosion, bluff retreat, loss of ecosystems, salinization of soils, ground and surface water, and impeded drainage will further increase along low-lying coasts worldwide without adequate adaptation efforts (IPCC, 2019).

Millions of residents, infrastructure, housing, natural resources, and economies in California's coastal counties face serious and costly threats from rising sea levels (LAO, 2020). The impacts of sea level rise will be amplified by storms, high tides, beach erosion and cliff retreat; flooding risks, in particular, will result from the combined effects of rising sea levels, heavy precipitation events, and shallower coastal groundwater (also due to sea level rise) (Barnard et al., 2019; Rahimi et al., 2020). Using a dynamic model (the Coastal Storm Modeling System or CoSMoS) that incorporates the effects of coastal storms in addition to estimates of sea level rise, projected areas of coastal flooding could impact over 600,000 people and $200 billion in property statewide over the next century (Figure 3; Barnard et al., 2019).

Critical infrastructure in many locations lies less than 4 feet above the high tide, including two international airports – Oakland and San Francisco – and about 172,000 homes (DWR, 2016). Rising sea levels place the airports, already vulnerable to storms and flooding, at greater risk (Griggs, 2020). Loss of service at either airport would result in major economic consequences regionally, nationally, and internationally (San Francisco Bay Conservation and Development Commission, 2012). Other critical infrastructure, such as ports, natural gas lines, and wastewater treatment plants, will also become more vulnerable to storms and flooding (Caldwell et al., 2013, CEC, 2017; Hummel et al., 2018). Notably, the areas projected to experience flooding events by 2100 contain at least 400 hazardous facilities including power plants, refineries, and industrial facilities. Sea level rise poses risks for such facilities experiencing flooding events that can potentially expose nearby residents to hazardous pollutants (UC Berkeley, 2021). Processes that result in significant short-term increases in water levels such as King tides (extremely high tides that typically occur a few times a year), seasonal cycles, winter storms, and patterns of climate variability (e.g., the Pacific Decadal Oscillation or the El Niño Southern Oscillation (ENSO)) cause the greatest impacts on infrastructure and coastal development due to the significantly higher water levels they produce compared to sea level rise alone (Griggs et al., 2017).

Low-income communities in California often are located in areas where infrastructure lack sufficient drainage capacity, making them particularly vulnerable to the impacts of flooding (Ramini et al., 2020). Climate-driven coastal hazards will amplify environmental justice-related inequities. Hazards in vulnerable areas disproportionately affect communities that are least able to adapt. For example, hazardous facilities at risk of flooding are disproportionately located in low-income communities and communities of color. Further, disadvantaged communities are over 5 times more likely to be located within 1 km of one or more hazardous facilities at risk of flooding in 2050, and over 6 times in 2100 (UC Berkeley, 2021).

Figure 3. Projected overland flood exposure over the next century in select locations across California based on results from the Coastal Storm Modeling System (CoSMoS)



Source: Barnard et al., 2019

(a) Study area for CoSMoS with insets. Examples of modeled flood extents for the 100-year coastal storm in combination with 0, 0.50, 1.00, 1.50, 2.00, and 5.00 meters of SLR; (b) San Francisco International Airport, (c) City of Pacifica, (d) Port of Los Angeles and Port of Long Beach, (e) Port of San Diego and San Diego International Airport, and (f) City of Del Mar. (Figure generated using ArcGIS v. 10.4.2, by Esri. Local base maps from ArcGIS Online, World_Terrain_Base, and ESRI_Imagery_World_2D, accessed 2 Oct 2018.) Projections can be viewed interactively and translated into socioeconomic exposure.

Compared to higher-income communities and property owners, people with lower incomes and residents of rental units face disproportionately greater impacts from sea level rise (CCC, 2015; LAO, 2020). They are more likely to be displaced by flooding or related impacts because they are not able to rebuild or are less able to prepare their residences for floods. They may be unable to evacuate and thus have less control over their safety. They may have less resources and are likely to not have insurance to replace lost or damaged property or structures. The loss of local public beaches and recreational areas would disproportionately affect low-income communities that have few options for low-cost recreation (CCC, 2015).

Figure 4. Cliff collapse at Isla Vista, California (taken 2005)

Credit: Patrick Barnard, USGS

Coastal erosion and cliff collapse (see Figure 4) threaten public safety, infrastructure, and property as they become more common with sea level rise (Vitousek et al., 2017; Limber et al., 2018; USGS, 2019). In Southern California, for instance, the projected sandy beach shoreline change indicates that 31 to 67 percent of Southern California beaches may become completely eroded by 2100 without human interventions (Vitousek et al., 2017). Further, sea cliffs could retreat at a rate nearly double that of the historical rate, causing an average total land loss of 19 to 41 meters (about 62 to 135 feet) by 2100 (Limber et al., 2018). As sea levels continue to rise, cliff collapses and the hazards they pose can also become increasingly common. In August 2019, three people were killed on a beach at Encinitas when the bluff above them collapsed, illustrating the damage a cliff collapse can cause.

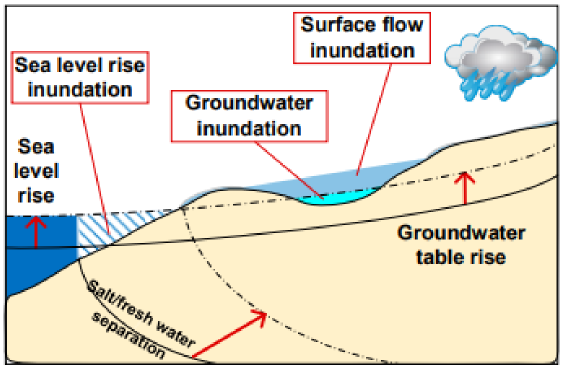
Figure 5. Olivella shells carved by the Chumash

Source: Science News, 2021

Coastal erosion and sea level rise, along with warming ocean temperatures and ocean acidification, collectively threaten cultural sites and resources along the shoreline for the Amah Mutsun and Chumash Tribes. Coastal erosion has damaged cultural sites, and as sea levels rise, sites previously used for gathering are no longer accessible (SCTLS, 2021; see Amah Mutsun and Santa Ynez Chumash Tribal reports). For example, traditional areas for the Chumash Tribe to gather Olivella shells (Figure 5), used in shell money, jewelry, and regalia, are often no longer accessible. Without access to traditional sites, knowledge can be disrupted, and the weight of that loss is felt by generations of tribal members (PBMI and SYBCI, 2021).

Furthermore, rising seas will result in shallower coastal groundwater, leading to emergent groundwater (when groundwater rises to or above the surface of the ground) in some places (Befus et al., 2020; USGS, 2020). This elevated groundwater can flood communities, damage infrastructure, and release pollutants, all before seawater overtops the beach. (Grant et al., 2021 May, 2020; Plane et al., 2019; Figure 6). Areas with emergent groundwater may occur progressively inland, expanding the area affected by sea level rise beyond what is anticipated solely from flooding caused by water flowing overland (May, 2020). A 2-meter rise in sea levels could lead to significant hazards from shallow and emergent groundwater in communities along California’s coast, potentially affecting 4 million residents and $1.1 trillion in property, 33,000 km of roads, and 3,000 critical facilities (such as schools, police stations, and hospitals), with 6 to 9 times greater population, property, and infrastructure exposure than overland flooding (Befus et al., 2020; Jones et al., 2017; USGS, 2021). Under a changing climate, surface flooding – resulting from sea level rise and episodic storm-driven waves, surge, precipitation, and river flows – and sea level rise-driven elevated groundwater levels can interact with each other and worsen the overall flood risk on coastal communities (Rahimi et al., 2020).

Figure 6. Emerging sources of inundations in coastal areas with climate change



Source: Rahimi et al., 2020

Groundwater elevation can affect communities in other ways as well. As higher ocean water levels force up water levels underneath the ground, saltwater can intrude into fresh groundwater supplies, potentially affecting drinking water quality. Toxic contaminants can leak to the surface or flow through the subsurface to also compromise drinking water sources. Contaminated lands located along the coast and bay at risk of both surface and groundwater flooding include active and closed landfills, as well as “brownfields” which are undergoing or require cleanup. Moreover, raw sewage can seep into fresh groundwater aquifers or back up into streets and homes (LAO, 2020). Seawater intrusion into aquifers may require local communities to rely on other groundwater basins for their water supply (Coastal Resilience, 2020).

Coastal ecosystems in California are also threatened by sea level rise, including beaches, wetlands, estuaries, and fisheries. These wildlife areas provide flood protection, water treatment, carbon sequestration, biodiversity, wildlife habitat, and recreation (CEC, 2009). The coastal environment also supports economically valuable commercial and recreational fishing activities (Caldwell et al., 2013).

The health of two such coastal ecosystems in California, sandy beach and tidal marshes, may plummet by 2050 without adequate adaptation and resilience strategies (Barnard et al., 2021; Myers et al., 2019). Predictions suggest that sea level rise will completely flood the mudflats at the San Pablo Bay estuary over the next 100 years, for instance (May 2020). This wildlife refuge protects the largest remaining contiguous patch of pickleweed-dominated tidal marsh in the northern San Francisco Bay, which provides critical habitat to the endangered salt marsh harvest mouse (Smith et al., 2018; US FWS, 2013). The combined effect of increased inundation and salinity projected under most climate change scenarios can significantly compromise pickleweeds and other plants important to the wetland habitats of the salt marsh harvest mouse (Smith et al., 2018).

Rising seas also present serious threats to the Sacramento-San Joaquin Delta. During storms and high-water flood events, higher sea levels increase the likelihood of Delta island levee failures, resulting in potentially catastrophic flooding to island communities and infrastructure. Sea level rise will increase the Delta's salinity, particularly during periods of reduced freshwater outflows from snowmelt. This puts the water supply for over half of California's population and much of the Central Valley's agriculture at risk. As previously mentioned, saltwater intrusion into groundwater may also increase with sea level rise, putting further pressure on limited drinking water supplies (DWR, 2013).

To assist with local adaptation strategies, online coastal flooding hazard maps using data produced by the scientific and research community in California may be accessed at: CalAdapt, Our Coast Our Future, Hazard Exposure and Reporting Analytics (HERA), and CoSMoS. These maps include predicted flooding for the San Francisco Bay, Sacramento-San Joaquin River Delta and California coast resulting from storm events at different sea level rise scenarios. Multiple efforts throughout California are underway to plan for, prepare, and adapt to rising seas and protect coastal ecosystems, infrastructure and communities (for examples, see CNRA, 2018 and 2021; OPC, 2021).

What factors influence this indicator?

As previously mentioned, human influence has very likely been the main driver of global sea level rise since at least 1971 (IPCC, 2021). Water from melting mountain glaciers and ice sheets is the main source of global mean sea level rise today (IPCC, 2019; Slater et al., 2020). The ice sheets in Greenland and Antarctica, while not expected to melt completely even on millennial time scales, contain enough ice to raise global mean sea level by 24 feet and 187 feet, respectively. In addition, the accelerating rate of ice loss from these ice sheets is of particular concern (Griggs et al., 2017).

Heat-driven expansion (also known as the steric effect) was the single greatest contributor to global mean sea level rise over the past century, accounting for about half of the observed sea level rise (Griggs, et al., 2017). The ocean has absorbed more than 90 percent of the excess energy associated with anthropogenic greenhouse gas emissions, leading to ocean warming. As the ocean warms, water expands, and sea levels rise (IPCC, 2019).

Other sources of land-based water that contribute to sea level include anthropogenic activities. Groundwater that is pumped for agriculture, industry, and drinking ultimately drives more water to the ocean, thereby raising the sea level along the California coast (Griggs, et al., 2017). Conversely, dam building along rivers and associated reservoir impoundment can lower the sea level; however, estimates for the past few decades suggest that the effect of groundwater depletion and dam/reservoir contribution to sea level rise are secondary factors and largely cancel each other (Cazenave and Cozannet, 2014).

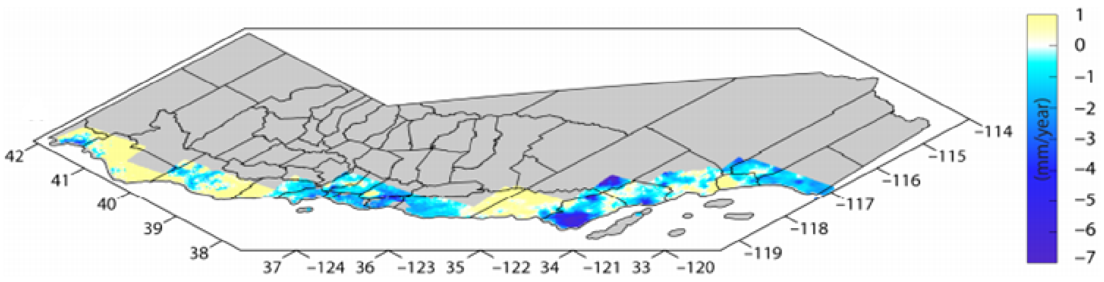
Global sea levels vary by region. Wind and water density gradients push sea levels higher in some places and lower in others. Climatic variability in different regions also affects local sea levels. ENSO in the eastern Pacific Ocean, for instance, produces alternating warm (El Niño) and cool phases (La Niña) that can bring sharp swings in sea level that are transient and typically last for only about a year. Additionally, ice sheets in Greenland and Antarctica, as well as mountain glaciers exert a gravitational pull on the ocean, resulting in a complicated distribution of sea level across the globe, called sea level fingerprints. When the ice melts, water that had once been pulled toward the ice mass due to gravitational attraction migrates away (NASA, 2017).

Understanding relative (local) sea level rise is important to understanding how low-lying coastal communities and ecosystems will be affected by flooding, wetland loss, and damage to infrastructure, and it can deviate from regional estimates of sea level rise, which typically don't resolve finer scale shifts in land movement. (Blackwell et al., 2020). Episodically, local sea level is modulated by processes that produce higher-than-normal coastal water levels, such as storm surge, wave effects, and spring and King tides. Over the long term, glacial isostatic adjustment (GIA) due to crustal loading/unloading and plate tectonics can play a significant role in regional and local sea levels. Additionally, fluid withdrawals from the subsurface (e.g., due to groundwater pumping and hydrocarbon withdrawal), as well as sediment compaction, can lead to high rates of local subsidence, as in the California Bay-Delta, and along the San Francisco Bay shoreline. Much of California's coast is subsiding due to regional changes in land levels.

A radar study of ~100 km wide swath of land along California's coast during the years 2007-2018 estimated that between 4.3 million and 8.7 million people in California's coastal communities live on areas of subsiding land (Figure 7; Blackwell et al., 2020). Many of the islands in the California Bay-Delta have dropped below sea level due to microbial oxidation and soil compaction caused by more than a century of farming (NASA, 2017). Conversely, plate tectonics can cause land uplift along the coast to outpace sea level rise, as is happening in Crescent City in northern California where

NOAA’s records show a drop in sea level over time. The far north coast is the only area along California where sea level is dropping relative to land surface (Russell and Griggs, 2012).

Figure 7. Exposure to land subsidence along the coast of California



Map showing vertical land movement rates, in mm/year (2007-2018), along California’s coast. Black lines identify California’s counties.

Source: Blackwell et al., 2020

Technical considerations

Data characteristics

Sea level measurements came from federally operated tide gages located along the California coast which are managed by the National Water Level Observation Network, within NOAA, as well as from satellite altimetry operated by NASA. Data are available online at NOAA’s Tides and Currents webpage and NASA’s sea level webpage.

Tide stations measure sea level relative to specific locations on land. Short-term changes in sea level (e.g., monthly mean sea level or yearly mean sea level) are determined relative to a location’s Mean Sea Level, the arithmetic mean of hourly heights observed over a specific 19-year period called the “National Tidal Datum Epoch” (NTDE) established by NOAA’s National Ocean Service. The NTDE accounts for the effect of the 18.6-year lunar nodal cycle on variations in the tidal range. The current NTDE is 1983-2001 (previous NTDEs were for the periods 1924-1942, 1941-1959, and 1960-1978); NTDEs are updated roughly every 20 years (NOAA, 2000; Szabados, 2008).

The U.S. federal government first started collecting measurements of sea levels in the mid-19th century to assist with accurate navigation and marine boundary determinations. Data from these early observation efforts and continued monitoring are used to assess long-term changes in sea level in multiple locations in California. Monitoring efforts have expanded over the years to include more locations with tidal stations, allowing for analysis of sea level trends at more regions, although for shorter time scales (NOAA, 2006).

Strengths and limitations of the data

Monthly mean sea levels tend to be highest in the fall and lowest in the spring, with differences of about 6 inches. Local warming or cooling resulting from offshore shifts in water masses and changes in wind-driven coastal circulation patterns also seasonally alter the average sea level by 8.4 inches (21 cm) (Flick, 1998). For day-to-day activities, the tidal range and elevations of the high and low tides are often far more important than the elevation of mean sea level.

As noted above, geological forces such as subsidence, in which the land falls relative to sea level, and the influence of shifting tectonic plates and glacial isostatic adjustment (GIA) complicate regional estimates of sea level rise. Much of the California coast is experiencing elevation changes due to tectonic forces and GIA. Mean sea level is measured at tide gauges with respect to a tide gauge benchmark on land, which traditionally was assumed to be stable. This only allows local changes to be observed relative to that benchmark. Additional data from global positioning systems (GPS) are useful to record vertical land movement at the tide gauge benchmark sites to correct for seismic activity and the earth's crustal movements. Satellites have been used since the 1990s to track sea level rise at the global scale with uniform coverage and provide an additional check on sea level rise rates derived from tide gauges alone (Abdalla et al., 2021; NOAA, 2020).

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