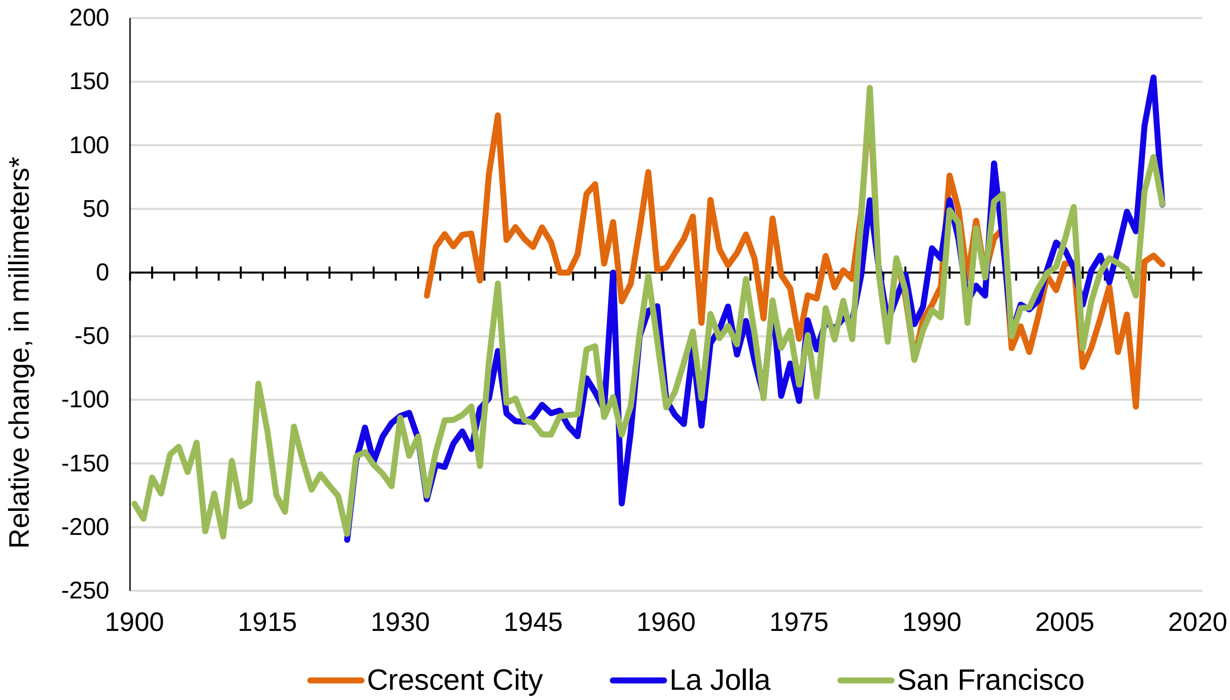
SEA LEVEL RISE

Sea levels along the California coast have generally risen over the past century, except along the far north coast where uplift of the land surface has occurred due to the movement of the Earth's plates.

Figure 1. Annual mean sea level trends



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

Source: NOAA, 2017

What does the indicator show?

Mean sea levels along the California coast show year-to-year variability, peaking during El Niño years (when the waters of the eastern Pacific Ocean are warmer). Over the long term, mean sea levels — the average height of the ocean relative to land — have been rising. Figure 1 shows annual changes relative to a standard elevation established by the National Oceanic and Atmospheric Administration (NOAA) as a reference point (see *Technical Considerations* for details).

Mean sea level has increased by 180 millimeters (mm) (7 inches (″) since 1900 in San Francisco, and by about 150 mm (6″) since 1924 in La Jolla. In contrast, sea level at Crescent City has declined by about 70 mm (3″) since 1933 due to plate tectonics. Levels at all three locations rose in 2014 and 2015, possibly due to unusually warm sea surface temperatures in the Pacific Ocean during that period.

Trends at 16 tide stations operated by NOAA in California are presented in Table 1, with graphs for individual locations in the Appendix (NOAA, 2017). (One NOAA tide station has been excluded from the table: Rincon Island, an artificial offshore island in

Ventura County built for oil and gas production, reported a linear trend of +3.22 mm/year based on measurements from 1962 to 1990.)

Table 1.
Sea Level Trends (as reported by NOAA)

Location	Period of record	Trend, mm/year (inches/year)
Alameda*	1939-2016	+0.72 (+0.03)
Arena Cove	1978-2016	+0.53 (+0.02)
Crescent City	1933-2016	-0.80 (-0.03)
La Jolla	1924-2016	+2.17 (+0.09)
Los Angeles	1923-2016	+0.96 (+0.04)
Monterey	1973-2016	+1.39 (+0.05)
Newport**	1955-1993	+2.22 (+0.09)
North Spit	1977-2016	+4.68 (+0.18)
Point Reyes	1975-2016	+1.98 (+0.08)
Port Chicago*	1976-2016	+1.58 (+0.06)
Port San Luis	1945-2016	+0.84 (+0.03)
Redwood*	1974-2016	+1.99 (+0.08)
San Diego	1906-2016	+2.15 (+0.08)
San Francisco	1897-2016	+1.94 (+0.08)
Santa Barbara	1973-2016	+1.01 (+0.04)
Santa Monica	1933-2016	+1.51 (+0.06)

* Gauge not along the outer coast
** Currently inactive

Source: NOAA, 2017

The general trend towards higher sea levels in California is consistent with global observations (IPCC, 2014). Global sea-level rise is the most obvious manifestation of climate change in the ocean (Griggs et al., 2017). Since the mid-19th century, global mean sea levels have been rising at a higher rate than during the previous two millennia. More recently, the rate of increase has been at 3.2 mm/year (about 0.1 inch/year) between 1993 and 2010, faster than the rate of 1.7 mm/year (0.07 inch/year) between 1901 and 2010, during which sea levels rose by 0.19 meters (7.5 inches) (IPCC, 2014). Similarly high rates occurred between 1920 and 1950.

Why is this indicator important?

More than 70 percent of California residents live and work in coastal counties, and almost 86 percent of the state's total gross domestic product comes from these counties (Caldwell et al., 2013). California's hundreds of miles of scenic coastline contain ecologically fragile estuaries, expansive urban centers, and fisheries that could be impacted by future changes in sea level elevation. Critical infrastructure 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. 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 natural gas lines, power plants, and wastewater treatment plants, will also become more vulnerable to storms and flooding (CEC, 2017; Caldwell et al., 2013).

The risks of flooding, coastal erosion, and shoreline retreat increase with rising sea levels. Short-term processes that result in significant short-term increases in water levels such as “King tides” (extremely high tides that typically occur during a new or full moon), seasonal cycles, winter storms and patterns of climate variability (e.g., the Pacific Decadal Oscillation or the El Niño Southern Oscillation (ENSO)) will likely continue to 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).

Rising sea levels can disrupt ecosystems along the coast, including wetlands, estuaries, and fisheries. These coastal ecosystems provide flood protection, water treatment, carbon sequestration, biodiversity, wildlife habitat, and recreation (CEC, 2009). The coast also supports economically valuable commercial and recreational fishing activities (Caldwell et al., 2013).

Rising seas 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. Sea level rise would tend to increase the Delta’s salinity, particularly during periods of reduced fresh water 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. Saltwater intrusion into groundwater may also increase with sea level rise, putting further pressure on limited drinking water supplies (DWR, 2013).

Coastal communities may lose revenue under extreme flood events (Caldwell et al., 2013). Hazards in vulnerable areas can disproportionately affect communities that are least able to adapt. Compared to higher-income communities and property owners, people with lower incomes and residents of rental units are more likely to be displaced by flooding or related impacts because they are not as able to rebuild, have less control over their safety, and have less access to insurance. Importantly, tribal communities are often tied to specific regions and cannot easily relocate. In addition, loss of local public beaches and recreational areas would disproportionately affect low-income communities that have few options for low-cost recreation (CCC, 2015).

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: http://beta.cal-adapt.org/. These maps show predicted inundation for the San Francisco Bay, Sacramento-San Joaquin River Delta and California coast resulting from storm events at different sea level rise scenarios.

What factors influence this indicator?

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, 2014). Heat-driven expansion accounts for about half of the sea level rise that occurred in the past one hundred years (Griggs, et al., 2017).

The other major contributor to sea level rise is water from melting mountain glaciers, ice caps, and polar ice sheets. Within days of ice water entering the ocean, regions around the globe experience a rise in sea level (IPCC, 2014). 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 to the large volume of water they contain, the accelerating rate of ice loss from these ice sheets is of particular concern (Griggs et al., 2017).

Other sources of land-based water that contribute to sea level include anthropogenic activities. Groundwater that is pumped for farming and drinking tends to end up in the ocean more than returning into the ground, thereby raising the sea level (Griggs, et al., 2017; Cazenave and Cozannet, 2014). 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 may 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 and cool phases that can bring sharp swings in sea level that are transient and do not last multiple decades. Additionally, ice masses around Earth's poles exert a gravitational pull. When the ice melts, water that had once been pulled toward the ice mass due to gravitational attraction migrates away (NASA, 2017).

In the short term, local sea level is modulated by processes which produce higher-than-normal rises of coastal waters, such as storm surges or exceptionally high tides known as King tides. Over the long term, subsidence and plate tectonics play a role in local sea levels. When the land itself sinks, as in the California Bay Delta, relative sea levels rise. 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).

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, part of what is now NOAA. Data are available online at https://tidesandcurrents.noaa.gov/.

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 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 United States 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

Due to astronomical forces, such as the lunar cycle, it is difficult to isolate possible changes due to global warming by looking at short time periods in the sea level tidal record. 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 (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. Shoreline damage due to wave energy is a factor of wave height at high tide and has a higher impact on the coast than mean sea level rise.

As noted above, geological forces such as subsidence, in which the land falls relative to sea level, and the influence of shifting tectonic plates complicate regional estimates of sea level rise. Much of the California coast is experiencing elevation changes due to tectonic forces. 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. There are studies in progress that will study the feasibility of monitoring absolute changes in sea level on a global scale through the use of global positioning systems (GPS) satellite altimetry. The GPS may be useful to record vertical land movement at the tide gauge benchmark sites to correct for seismic activity and the earth's crustal movements.

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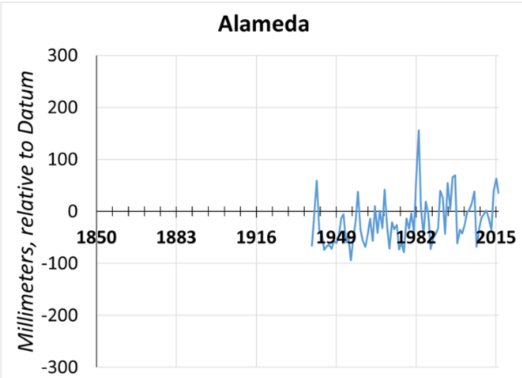
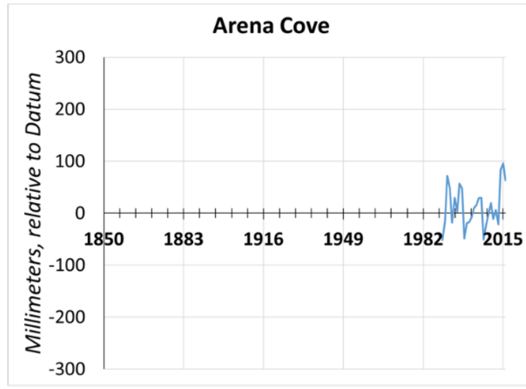
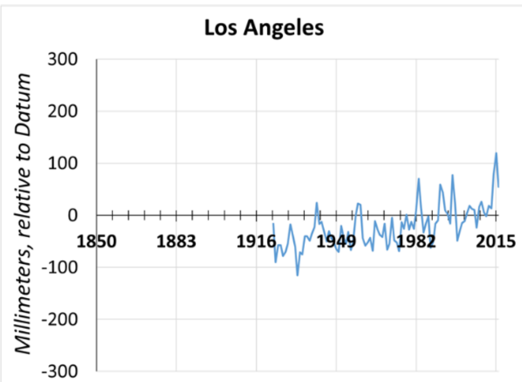
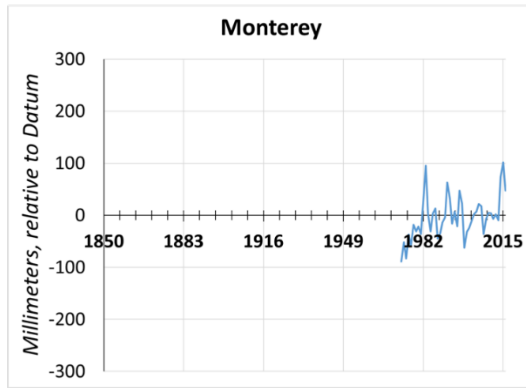
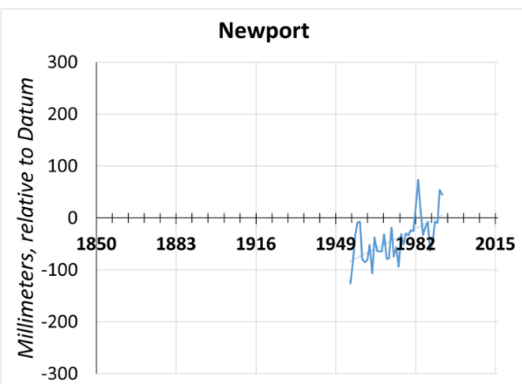
APPENDIX. Mean sea level trends for 16 California tide stations (data from NOAA, 2017)

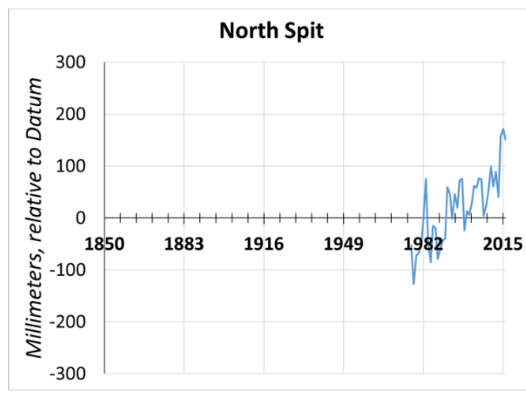


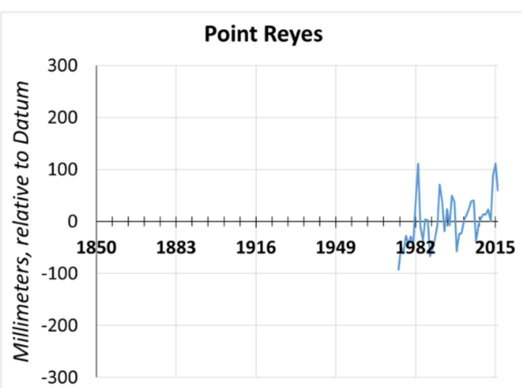


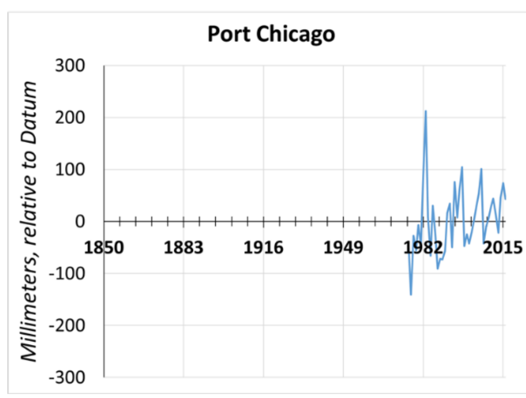


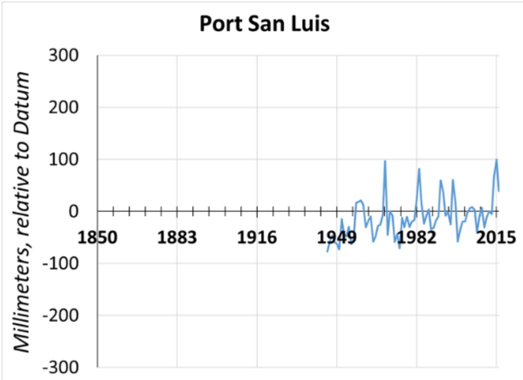











Port San Luis
Millimeters, relative to Datum
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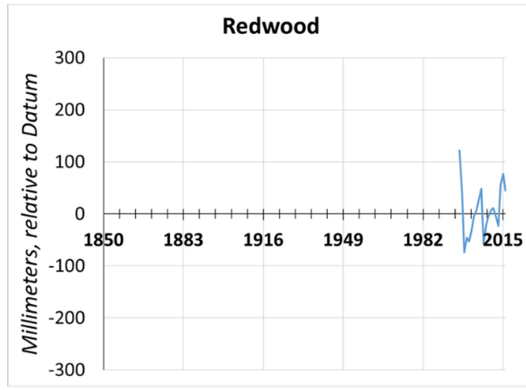
-200
-300
1850
1883
1916
1949
1982
2015


Redwood
Millimeters, relative to Datum
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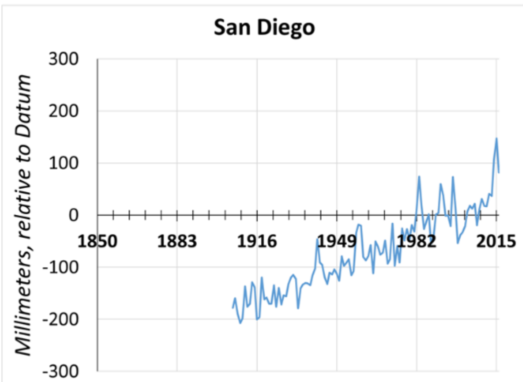
0
-100
-200
-300
1850
1883
1916
1949
1982
2015


San Diego
Millimeters, relative to Datum
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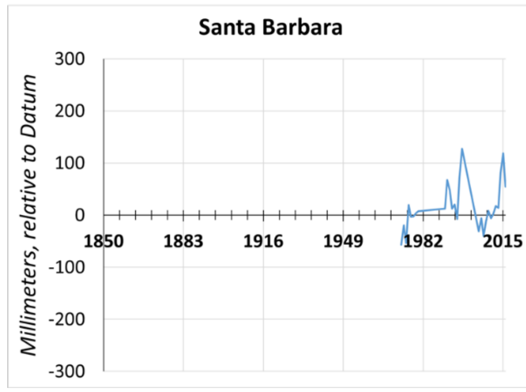
1916
1949
1982
2015


Santa Barbara
Millimeters, relative to Datum
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1982
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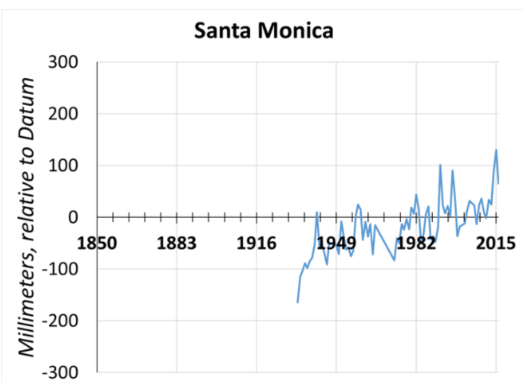
Santa Monica
Millimeters, relative to Datum
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100
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-100
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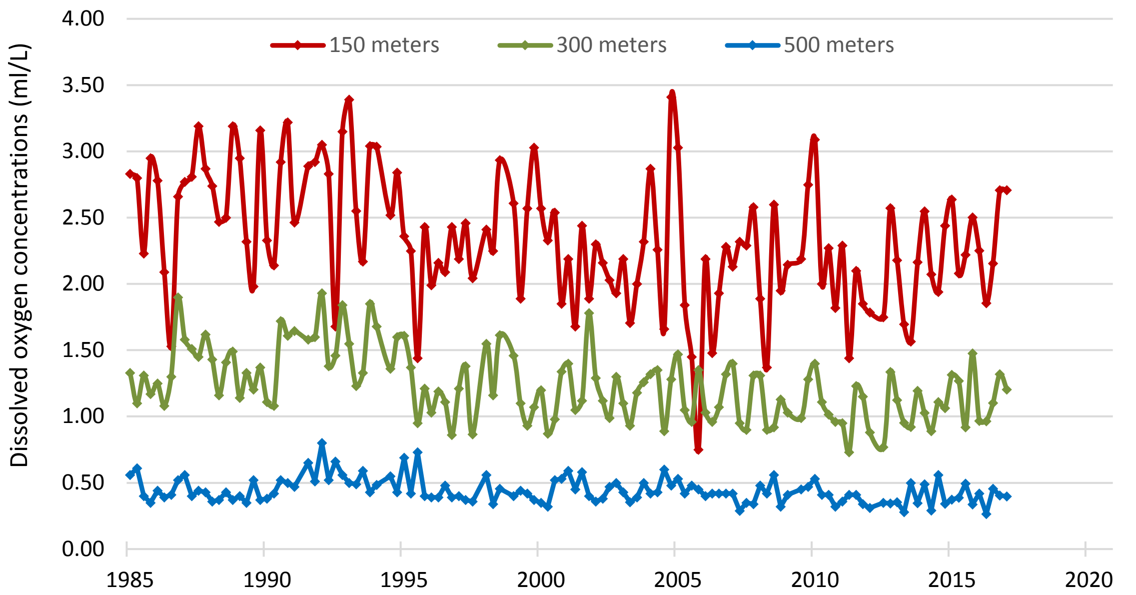
1850
1883
1916
1949
1982
2015

DISSOLVED OXYGEN IN COASTAL WATERS

Dissolved oxygen concentrations are declining in ocean waters off southern California.

Figure 1. Dissolved oxygen concentrations at three water depths, 1985-2017* off the San Diego coast (CalCOFI station 93.3 30)



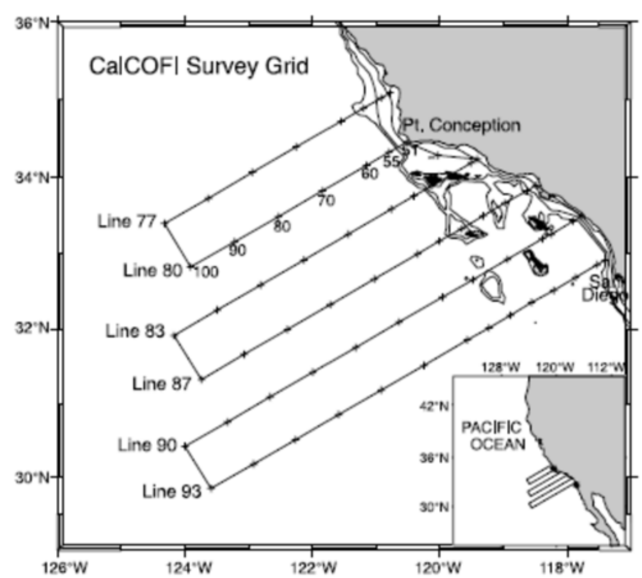
Source: CalCOFI, 2017

* *Values shown are quarterly averages of oxygen concentrations measured at this location.*

What does this indicator show?

Instrumental measurements of dissolved oxygen (DO) concentrations point to decreasing oxygenation of coastal waters within the California Current. As shown in Figure 1, DO concentrations at three water depths offshore of San Diego indicate overall mean decreases as well as significant low-oxygen events since the mid-1990's. The measurements were taken by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) as the location "Line 93.3, station 30" shown in Figure 2. This location is where the influence of the California Undercurrent is typically observed. This current is a

Figure 2. Map showing location of Line 93



Source: Bograd et al., 2008