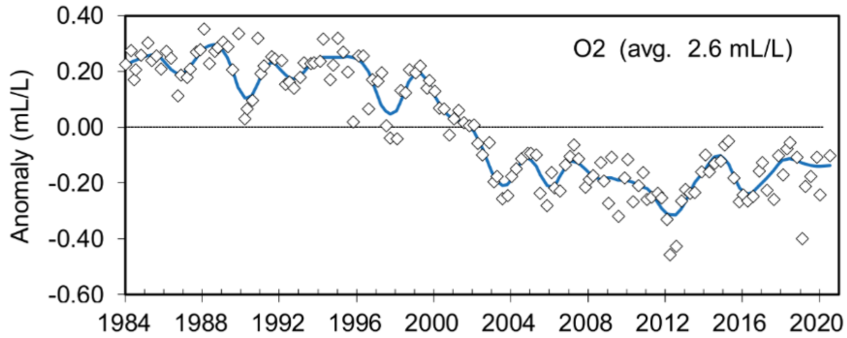
DISSOLVED OXYGEN IN COASTAL WATERS

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

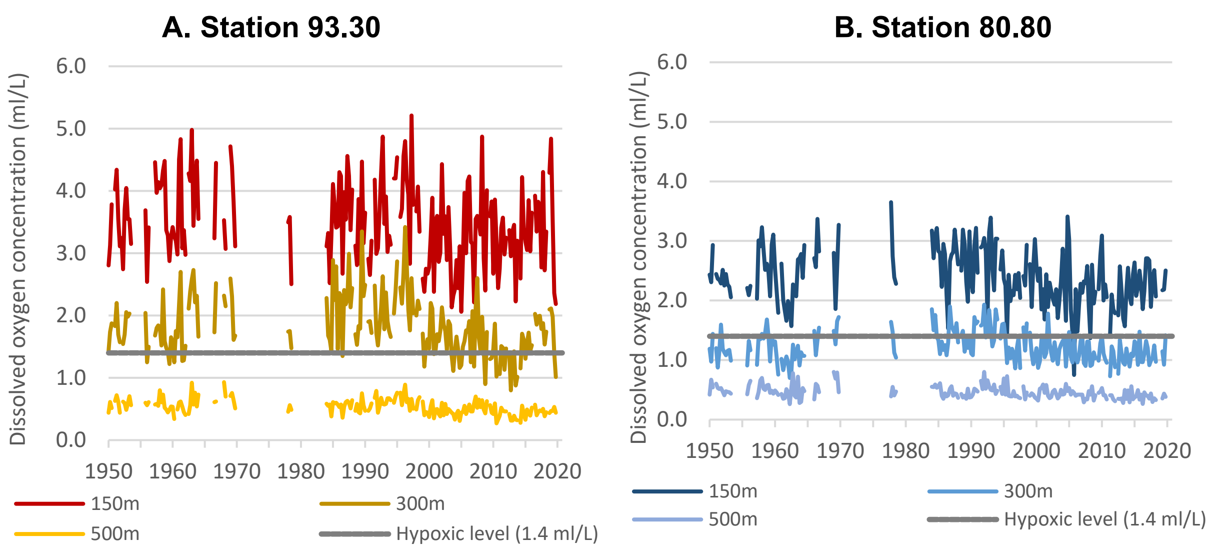
Figure 1. Dissolved oxygen concentrations across 66 monitoring stations in Southern California waters (1984-2020)



Source: Weber et al., 2021 Supplementary Figure 6

Each diamond on the graph represents the anomaly, or the difference between the average dissolved oxygen concentrations measured across 66 stations and the long-term average of 2.6 mL/L (based on values from a baseline period 1984 to 2013). The solid blue line connects annual averages. The stations are shown on the Figure 3 map; measurements were taken on the σ_θ=26.4 kg/m^3 isopycnal, the depth at which seawater is at a density of 1026.4 kg/m^3.

Figure 2. Dissolved oxygen concentrations at two monitoring stations on the Southern California Coast (1950-2019)



Source: CalCOFI, 2021a

Quarterly averages of dissolved oxygen concentrations in milliliters per liter (ml/L) measured at three depths (150, 300 and 500 meters) at Line 93, station 30 and Line 80, station 80 (see map, Figure 3).

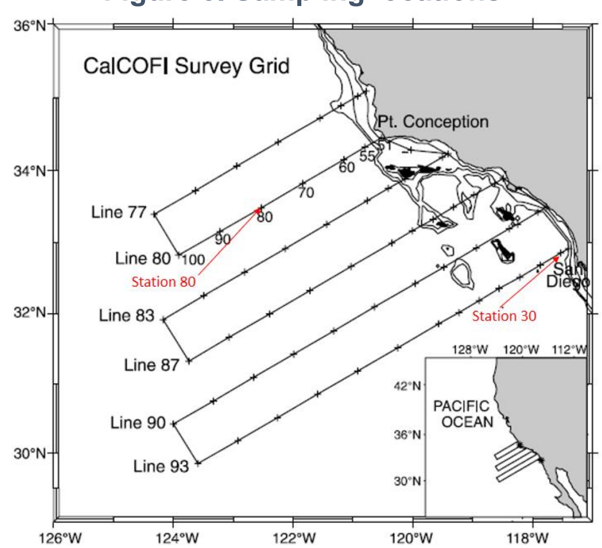
What does this indicator show?

Instrumental measurements of dissolved oxygen (DO) concentrations point to increasing deoxygenation of coastal waters within the California Current in recent decades (Figures 1 and 2; also Bograd et al., 2019; Evans et al., 2020; Weber et al., 2021). The California Current extends from British Columbia, Canada to Baja California, Mexico. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) has been taking measurements of DO periodically off southern California from San Diego to Point Conception since 1950, and consistently at a grid of stations four times per year since 1984 (see Figure 3 for locations). Figure 1 is based on measurements from the 66 core stations in the CalCOFI survey area. Figure 2 presents data collected from three depths at two stations: [A] Line 93, station 30 (93.30), and [B] Line 80, station 80 (80.80).

Throughout CalCOFI survey area, at depths corresponding to the "σ_θ-26.4 isopycnal" – the depth at which seawater is at a density of 1026.4 kg/m^3 – DO concentrations decreased significantly from about between the mid-1990s and the mid-2000s (Figure 1; also Bjorkstedt et al. 2012 as cited in Thompson et al., 2019). Following this decline, DO concentrations have been relatively constant, remaining below the long-term average since (Weber et al., 2021). Overall, DO concentrations in this region (to at least 500 m depth) have mostly declined to values lower than observed in the 1950's to 1960's (Bograd et al., 2008, 2015, 2019).

Figure 2A shows DO concentrations at three water depths at Station 93.30 offshore of San Diego. The data indicate overall mean decreases with minimal changes in the mean in the past 10 years. Since the mid-1990's, significant low-oxygen events have been observed: concentrations were below the hypoxic level (<1.4 ml/L), which can potentially cause physiological stress in marine organisms. This location is representative of the influence of the northward-flowing California Undercurrent, which is a major supplier of deeper source waters (200 to 500 meters (m)) to the region and has a large influence on oxygen content for much of the survey area. At 80.80 off Point Conception, within the core of the near-surface, southward-flowing California Current, DO concentrations have also declined sharply since the mid-1990's but have been generally increasing at 150-300 m in the past five years.

Figure 3. Sampling locations



Modified from Bograd *et al.*, 2008

Why is this indicator important?

Declining DO concentrations in ocean waters and the associated changes in the depth and extent of low oxygen zones can lead to significant and complex ecological changes in marine ecosystems, including wide-ranging impacts on diversity, abundance, and trophic structure of communities (e.g., Levin et al., 2009; Somero et al., 2015; Stramma et al., 2010). Changing ocean chemistry, in concert with changes in temperature, may lead to even greater and more diverse impacts on coastal marine ecosystems (e.g., Somero et al., 2015).

Globally since 1950, more than 500 coastal sites have been reported to have experienced hypoxic conditions. Fewer than 10 percent of these were known to have hypoxia before then (Breitburg et al., 2018). Separate from these episodic hypoxic events, coastal California is characterized by the presence of a zone of depleted oxygen concentrations (Oxygen Minimum Zone, or OMZ) at depths from 600 to 1100 meters. The OMZ near California is expanding both vertically (moving upward towards the ocean surface (e.g., Bograd et al., 2008)) and horizontally (Somero et al., 2015). The declines in oxygenation observed off California are consistent with an observed expansion of the low oxygen zones elsewhere around the world (Breitburg et al., 2018; Stramma et al., 2008).

The expansion of oxygen-deficient zones can lead to a compression of favorable habitat for certain marine species and an expansion of favorable habitat for others. For example, following the 1997-98 El Niño event, the Humboldt squid (*Dosidicus gigas*) — which thrives in low-oxygen environments — expanded its range northward from Baja California to southeast Alaska, a shift that may have been affected by changes in the extent of oxygen-deficient zones (Gilly and Markaida, 2007). Studies have indicated that low-oxygen waters can reach nearshore coastal habitats via upwelling, with potential impacts on these habitats (Chan et al., 2019).

Oxygen plays a role in the cycling of nutrients such as nitrogen, phosphorus and iron. As a result, changes in oxygen levels can influence nutrient budgets, biological productivity and carbon fixation. In oxygen-depleted waters, anaerobic microbial processes can produce chemicals such as hydrogen sulfide, which is toxic to other organisms, and methane, a potent greenhouse gas (Breitburg et al., 2018).

What factors influence this indicator?

DO levels reflect a complex interplay between physical and biological drivers in the marine environment, including currents, upwelling, air-sea exchange, and biological productivity, respiration and decomposition. Warmer waters hold less oxygen, as the gas becomes less soluble, and surface warming produces stratification that reduces the overturning circulation essential in ocean ventilation processes. Warming also accelerates the rate of oxygen consumption by marine organisms (e.g., Breitburg et al, 2018; Somero et al., 2015). In addition to these processes, DO is influenced by high surface productivity, regional circulation of the North Pacific Ocean, and anthropogenic nutrient inputs to the coastal ocean, as discussed below.

Upwelling is a wind-driven physical process wherein deep, nutrient rich waters move upward into the shallow surface ocean. There is evidence that upwelling has increased in some locations along the California coast due to anthropogenic impacts (García-Reyes and Largier, 2010; Wang et al., 2015). Upwelling brings nutrient rich waters to the surface, where it drives surface ocean productivity (photosynthesis). The amount of surface water productivity affects DO concentrations because as biological material sinks downward from the surface ocean and decays, oxygen is utilized in the decay and decomposition process. Thus, DO concentrations decrease in the subsurface below regions of high biological productivity.

DO concentrations are also controlled by regional and global oceanographic processes. For example, the Southern California Bight – the 400 miles of coastline from Point Conception in Santa Barbara County to Cabo Colnett, south of Ensenada, Mexico -- is impacted seasonally by the northward-flowing California Undercurrent. Much of the Bight is included in the CalCOFI survey region. Declining oxygen concentrations in this region imply a change in the properties of equatorial source waters (Bograd et al., 2015, 2019). A recent study estimated that equatorial waters transported via the California Undercurrent accounted for 81 percent of the deoxygenation trend in the CalCOFI region since 1993 (Evans et al., 2020).

Local nutrient inputs from human practices (e.g., agriculture, wastewater discharge) can also decrease oxygen concentrations in coastal waters. Fertilizers and nutrient enrichment from wastewater promote algal growth. As this material sinks and decays, it can create localized areas of low oxygen. Management of coastal pollution is an important aspect of minimizing changes in oxygen concentrations on a local scale.

Scientists estimate that about 15 percent of global oxygen decline between 1970 and 1990 can be explained by ocean warming and the remainder by increased stratification. In coastal areas, especially nutrient-enriched waters, warming is predicted to exacerbate oxygen depletion (Breitburg et al., 2018). In its Sixth Assessment, the Intergovernmental Panel on Climate Change concluded that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and that deoxygenation will continue to increase in the 21st century (IPCC, 2021).

Technical considerations:

<u>Data characteristics</u>

This indicator is based on data from the CalCOFI program. Established in 1949, CalCOFI conducts quarterly cruises (18 to 28 days long) to measure the physical and chemical properties of the California Current System and census populations of organisms from phytoplankton to avifauna. Data collected at depths down to 500 meters include temperature, salinity, oxygen, phosphate, silicate, nitrate and nitrite, chlorophyll, phytoplankton and zooplankton biodiversity, and zooplankton biomass (CalCOFI, 2021b).

DO measurements for CalCOFI Line 93.3, Station 30.0 (offshore of San Diego) and Line 80, Station 80 (within the offshore California Current core) were downloaded from the CalCOFI website. Quarterly averages were derived from oxygen concentrations reported for that calendar quarter. While sampling did occur between 1950 and1980, there are data gaps during this period.

Strengths and limitations of the data
Very few datasets describe DO conditions north of San Francisco and/or in coastal regions. One analysis suggests that 20-30 years of data are needed to robustly detect long-term declines in DO above natural variability (Henson et al., 2016). All of the CalCOFI datasets meet this criterion, thus CalCOFI currently represents the best resource for distinguishing long-term trends in DO from natural variability. CalCOFI has limited sampling availability in nearshore/coastal habitats, so establishing additional coastal monitoring sites may be critical for characterizing DO conditions in these areas.

These observations are limited by sites where oxygen concentration measurements are currently monitored along the coast and do not reflect oxygen declines that may be occurring across the entire California Current System. As described above, the observed DO concentrations could be influenced by both local thermodynamic or biological processes, as well as remote, large-scale changes. The oxygen concentrations can vary with the depth, temperature and time of year DO levels are measured.

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