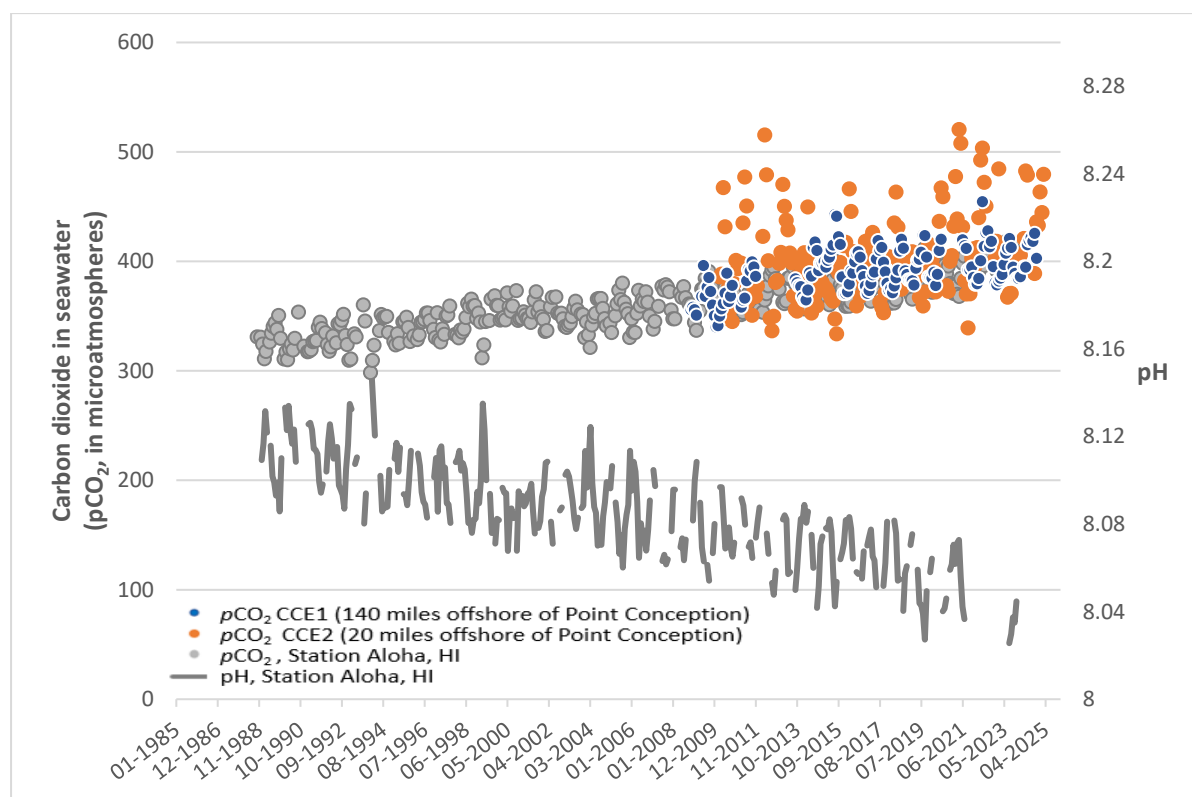


3.1 Ocean Acidification of California Waters

As atmospheric concentrations of carbon dioxide (CO_2) increase, so do concentrations in the ocean, part of a process known as “ocean acidification.” While long-term data for California waters are limited, CO_2 measurements at one offshore location near Point Conception are similar to those from long-term monitoring in Hawaii. They show increases in seawater CO_2 concentrations accompanied by increasing acidity (measured as pH). This phenomenon has been observed at multiple sites throughout the global ocean.

Figure 3.1.1. Seawater CO_2 and pH off Hawaii and California.



The figure shows CO_2 (measured as the partial pressure of CO_2 ($p\text{CO}_2$) in seawater) from two offshore California sites (CCE1 blue, and CCE2, orange). Data from the Hawaii Ocean Time-series (HOTS) are also shown in grey to provide a long-term reference record. Source: Hawaii Ocean Time-Series 2025, Dore et al. (2009); NOAA NCEI (2025); Sutton et al. (2012)

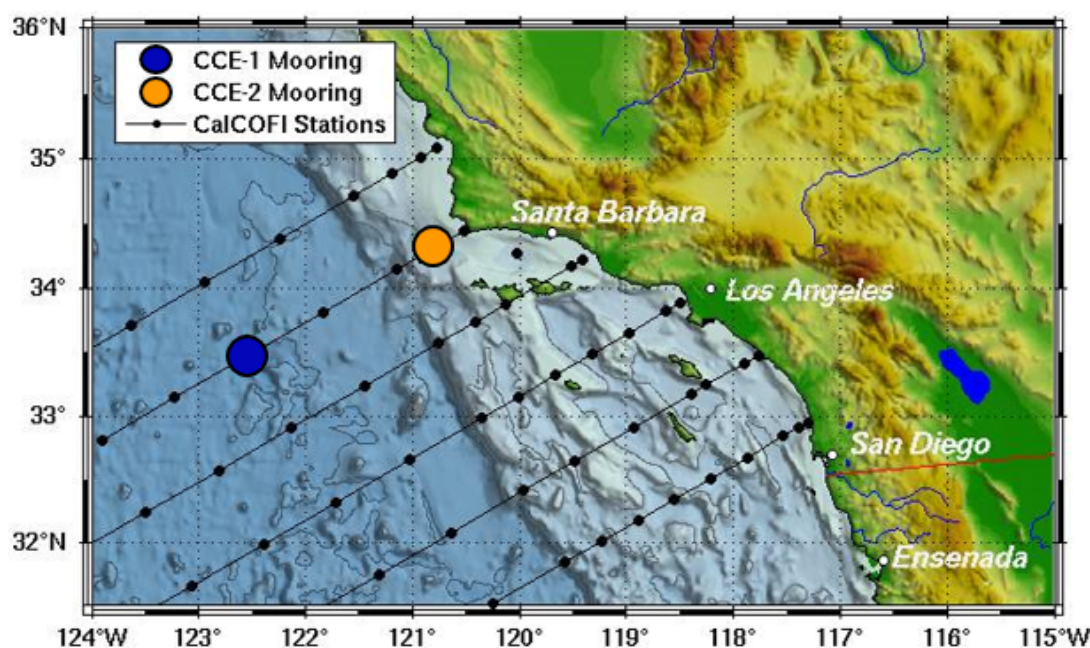


What does the indicator show?

The indicator shows increasing seawater CO₂ concentrations and decreasing pH concentrations measured offshore in California (**Figure 3.1.1**), consistent with ocean acidification observed globally. Concentrations of CO₂ are expressed as the partial pressure of carbon dioxide in seawater, or $p\text{CO}_2$. Off the coast of California, $p\text{CO}_2$ concentrations measured since 2008 at “CCE1” (see **Figure 3.1.2** for locations of monitoring sites) generally track those measured at Station Aloha where the Hawaii Ocean Time-series measurements are made, and consistent with increasing surface seawater $p\text{CO}_2$ concentrations observed at other open ocean time-series locations (**Figure 3.1.1**; Bates et al., 2015). At CCE2, a second mooring located approximately 20 miles from Point Conception, $p\text{CO}_2$ concentrations show greater variability, spanning 330–520 microatmospheres (μatm), reflecting the influence of seasonal upwelling at this more coastal location (Sutton et al., 2019; also see *Coastal Ocean Temperature* chapter). Upwelling is the wind-driven movement of deep, cool, carbon- and nutrient-rich ocean water to the surface, replacing the warmer, usually nutrient-depleted, lower CO₂ surface water.

Measurements at CCE1 began in September 2010 and provide the longest-running publicly available data on CO₂ concentrations in seawater offshore from California (there is a 21-month gap in measurements at CCE2). $p\text{CO}_2$ concentrations at CCE1 increased steadily from 2010 to 2024 at an average rate of approximately 2.6 μatm per year. At CCE2, $p\text{CO}_2$ increased at an average rate of approximately 2.0 μatm per year from 2010 to 2023 (not enough data for the year 2024 was available at the time of analysis).



Figure 3.1.2. Location of CO₂ Monitoring Sites.

Source: Modified from SIO (2026)

At Station Aloha, $p\text{CO}_2$ concentrations have increased steadily at the rate of approximately $1.8 \mu\text{atm}$ per year, and pH has decreased at the rate of 0.002 unit per year from 1985 to 2025. Global measurements show similar long-term changes (Bates et al., 2015; Bates and Johnson, 2023). Monitoring at Station Aloha off Hawaii provides the longest-running measurements of ocean acidity in the North Pacific Ocean.

Why is this indicator important?

CO₂ is the largest and most important anthropogenic driver of climate change. It is continuously exchanged between land, the atmosphere, and the ocean through physical, chemical, and biological processes. The global net uptake of CO₂ by the ocean is estimated at 29% of the total CO₂ emissions in the past decade (Friedlingstein et al., 2025), significantly reducing the accumulation of CO₂ in the atmosphere and some of the impacts of global warming (Rhein et al., 2013). As CO₂ concentrations in the ocean increase, carbonate ions (fundamental 'building blocks' for organisms that form shells or skeletons) decrease (Mekkes et al., 2021; Osborne et al., 2020; Rose et



al., 2020; Swezey et al., 2020). Economically and ecologically important West Coast species affected by ocean acidification include oysters, mussels and crabs (Chan et al., 2016). Marine species that are sensitive to ocean acidification include the California mussel (*Mytilus californianus*), krill, pelagic snails, and sea urchins (Bednaršek et al., 2022; Cooper et al., 2017; deVries et al., 2024; Gaylord et al., 2018; Harianto et al., 2021). Changes in species assemblages in southern California coastal waters and sediments suggest that the distributions of ichthyoplankton (fish eggs and larvae) and benthic invertebrate species have shifted – across water depths and north–south – due to warming and increasing acidification exposure since the 1970s–1980s (McClatchie et al., 2016; Gillett et al., 2023).

Tribal Connection 3.1.1

“Ocean acidification is also a concern for the Wiyot Tribe as it threatens low-lying cultural sites and many estuarine flora and fauna of great importance, including shellfish. While research is ongoing, there is some evidence that Wigi [Humboldt Bay] itself demonstrates a buffering effect against the otherwise rising acidity (lowering of pH) of the ocean. There are several hypotheses for this observation, one of which is that eelgrass plays a critical buffering role, underscoring its ecological importance (Barriquand et al., 2023).” (Wiyot Tribe, 2026).

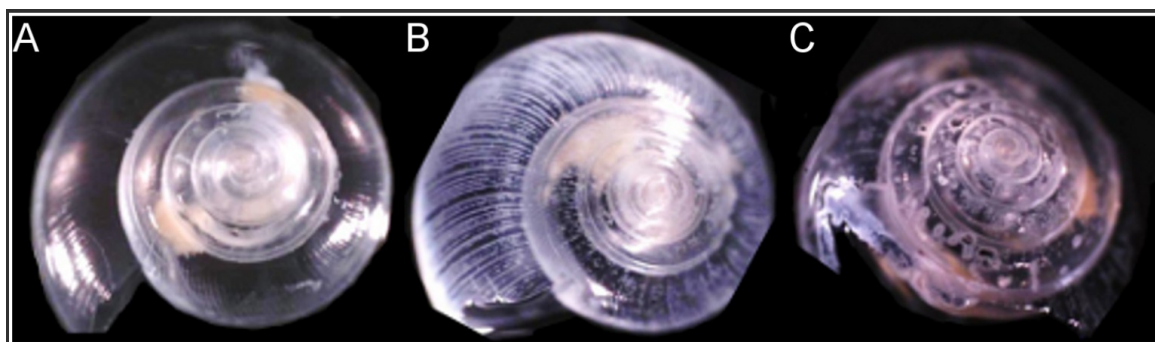
In Tribal listening sessions, several tribes, including the Coastal Band of the Chumash Nation and the Santa Ynez Band of Chumash Indians have reported that they have seen a decrease in abalone (a cultural keystone species), Pismo clams and Olivella shells due to ocean acidification (Pala Band of Mission Indians and Santa Ynez Band of Chumash Indians, 2021).

Other effects of acidification on coastal ecosystems include: indirect effects on marine food webs through sensitive calcifying prey species, such as sea snails (pteropods, also referred to as pelagic snails), and single-celled amoeboid organisms called foraminifera; degradation of the habitat provided by corals, mussels, oysters and other structure-forming calcifiers; and reduction of water filtration services provided by bivalves (Feely et al., 2016; Hollarsmith et al., 2020; Osborne et al., 2020; Mekkes et al., 2021).



Lower pH conditions can disrupt acid-base balance in marine organisms, affecting the physiology and behavior of marine species (Leung et al., 2022). Broader ecological consequences include trophic mismatch (Kroeker et al., 2021) and altered predator-prey and other species interactions, such as herbivory and competition (Ferrari et al., 2011; Kroeker et al., 2014; Sanford et al., 2014; Gaylord et al., 2018; Magel et al., 2020; Hodgson et al., 2018; Contolini et al., 2020; Lord et al., 2019).

Figure 3.1.3. Dissolution of Pelagic Snail Shells Exposed to Corrosive Seawater.



Images of *Limacina helicina*, a pelagic snail, after week-long incubation in Puget Sound waters at the following concentrations of aragonite (a form of calcium carbonate, Ω_a): [A] $\Omega_a \sim 1.59$, corresponding to current summer surface conditions; [B] $\Omega_a \sim 0.56$, current deep water or surface conditions during upwelling; and [C] $\Omega_a \sim 0.28$, future deep water or surface conditions during upwelling. Corrosion is evident on the ribs of the shell in [B], and [C] shows shell perforations. Source: Busch et al. (2014)

What factors influence the indicator?

The Intergovernmental Panel on Climate Change (IPCC) concluded in its Sixth Assessment Report that the uptake of anthropogenic CO₂ emissions is the main driver for the global decline in ocean water pH over the last 40 years (Gulev et al., 2021). The air-sea exchange of CO₂ is largely determined by the difference in the partial pressure of CO₂ between the atmosphere and the ocean surface; as the partial pressure of CO₂ in the atmosphere increases with increasing emissions, the ocean absorbs more of it to reach equilibrium. Long-term measurements of ocean carbon content at seven monitoring sites around the globe collectively show consistent and coherent changes in

the uptake of CO₂ by the ocean. At decadal timescales, ocean acidification rates in open ocean surface waters generally track atmospheric CO₂ increase (Bates et al., 2015; Cooley et al., 2022).

The magnitude of the air-sea CO₂ difference is also influenced by biological processes. Photosynthesis and respiration remove and add CO₂ to seawater, respectively. In coastal habitats, kelp forests and seagrass meadows can locally reduce high CO₂ concentrations by removal of CO₂ via photosynthesis; these effects, however, are temporary (Hirsh et al., 2020; Ricart et al., 2020). Shell formation by marine calcifiers also affects the carbonate chemistry of surrounding seawater by reducing buffering capacity and increasing *p*CO₂, while shells dissolving in seawater decrease *p*CO₂.

While biological processes and climate variability (e.g., the El Niño and La Niña events) play important roles in determining short-term (daily to seasonal) to interannual variability in surface ocean pH and *p*CO₂, respectively (Hofmann et al., 2011; Nam et al., 2011), ocean uptake of anthropogenic CO₂ drives longer-term decadal trends.

California's coastal waters are experiencing more acidified and lower oxygen conditions earlier than many regions as ocean acidification adds to naturally high concentrations of carbon dioxide resulting from the combination of upwelling and global ocean circulation processes (Feely et al., 2008; Hauri et al., 2009; Gaylord et al., 2018; Hodgson et al., 2018; Osborne et al., 2020). Along the Central California coastline, the continental shelf is wider, leading to greater retention of seawater on the shelf, where respiration further enhances CO₂ and reduces oxygen, leading to longer, more intense exposure to ocean acidification and low oxygen conditions (Damien et al., 2024; Hickey and Banas, 2008; Siedlecki et al., 2015; Feely et al., 2024). The California Current System has experienced amplified acidification over the past century, driven by the interaction between the elevated natural CO₂ concentrations and anthropogenic CO₂ (Arroyo et al., 2022; Stoll et al., 2025), with significant variation in hypoxia and ocean acidification exposure across habitats due to variability of upwelling and other circulation processes along the coast and through seasons (Cheresh and Fiechter, 2020). On interannual–decadal timescales, large-scale climate oscillations such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation can alter surface ocean CO₂



concentrations through basin-scale changes in oceanic and atmospheric circulation (Di Lorenzo et al., 2015), which in turn affect physical-biological processes and interactions among them (Chavez et al., 2007; Lilly et al., 2019).

The variability in $p\text{CO}_2$ concentrations in coastal waters (CCE2) compared to open ocean waters (CCE1) reflects the more complex acid-base chemistry dynamic of coastal waters (Sutton et al., 2019). In addition to upwelling and other climate-related processes, coastal waters are influenced by localized freshwater and atmospheric inputs, organic matter and nutrients from land, and processes in the underlying sediments. Similar variability has been observed at other monitoring stations along the California coast (e.g., M1 mooring in Monterey, Hog Island Oyster Company store station, Carlsbad Aquafarm shore station) (CenCOOS (Monterey), 2021; Chavez (Monterey), 2017; GOA-ON Explorer (shore stations), 2026; see references for URLs to access data from these stations). Knowledge of short-term variability of CO_2 in seawater is important to interpret changes attributed to anthropogenic processes at a given location. An analysis of $p\text{CO}_2$ and pH data collected at 40 monitoring stations (in four ocean basins, representing a range of ocean, coastal and coral reef locations) estimated the length of the record needed to distinguish anthropogenic trends from natural variability to be 8–15 years at open ocean sites (such as CCE1, estimated at 12 years) and 16–41 years at coastal sites (such as CCE2, estimated at 24 years), with a significant trend now having emerged at CCE1 (Sutton et al., 2019). $p\text{CO}_2$ is currently increasing at a rate of approximately 0.8 μatm per decade at CCE1.

Because changes in the ocean interior occur slowly, the ocean is already “committed” to changes resulting from current atmospheric greenhouse gas concentrations, even after concentrations stabilize; thus, ocean acidification is irreversible on timescales relevant to human societies and ecosystems (IPCC, 2019).

Technical considerations

Data characteristics

Monitoring along the California coast includes moorings with carbon dioxide and pH sensors, regular measurements of inorganic carbon variables on oceanographic cruises, calculation of aragonite saturation state, and shore-based observations of



carbon chemistry in nearshore waters. These monitoring efforts are part of larger scale monitoring programs, including the US Integrated Ocean Observing System (IOOS) and the National Oceanic and Atmospheric Administration (NOAA) ocean acidification observing network, and are conducted in collaboration with a wide range of international, national, and regional partners. Many of these efforts can be viewed in real time through an online data portal (GOA-ON Explorer, 2026).

Integrated biological, chemical, and physical oceanographic monitoring help identify ecosystem responses to ocean acidification and climate change. Long-term ecological monitoring programs for intertidal and subtidal ecosystems (e.g., [LiMPETS](#), [MARiNe](#), and [PISCO](#)), the Marine Protected Area Monitoring efforts (e.g., [Ocean Science Trust](#)), and oceanographic monitoring by the [Applied California Current Ecosystem Studies \(ACCESS\)](#) provide essential data to support a better understanding and interpretation of the impacts of ocean acidification for California.

The CCE1 mooring (140 miles southwest of Point Conception) was deployed in November 2008 as part of a multi-investigator, multi-disciplinary project by NOAA's Pacific Marine Environmental Laboratory. The project expanded to include the CCE2 mooring, at the shelf break, closer to Point Conception, in 2010. Sensors on these moorings measure aspects of biological, chemical, and physical oceanography as well as meteorology every three hours. This project is closely coordinated with other projects off of Southern California such as the [California Cooperative Oceanic Fisheries Investigations](#), and the [California Current Ecosystem Long Term Ecological Research](#).

Figure 3.1.1 features data from the Hawaii Ocean Time-series (HOTS) program for comparison. Since October 1988, this program has conducted observations about once per month of water column chemistry and biology at Station ALOHA, 62 miles north of Oahu, Hawaii. HOTS pH and $p\text{CO}_2$ values are calculated from measured parameters, with direct pH measurements also collected at sea.

Despite the central importance of direct measurements for detecting long-term changes in the ocean's carbon system, coordinated observing networks in the United States coastal and estuarine waters did not exist until the early 2010s, following the establishment of NOAA's Ocean Acidification Program (Jewett et al., 2020; Kennedy et



al., 2024). Historically, assessments of changes to the carbonate system relied on a handful of data records worldwide (none of which operated in California waters, and the longest of which began only in the early 1980s) (Bates et al., 2015). Recent studies have focused on ways in which to build monitoring frameworks and identify gaps (e.g., Turk et al., 2019; Taylor-Burns et al., 2020; Zulian et al., 2025).

Strengths and limitations of the data

Observational time-series are publicly available from only two moorings in southern California locations, and do not provide coverage of acidification conditions in many central and northern California coastal ecosystems, nor in nearshore or subsurface habitats. As a result, these data may not fully capture the spatial variability in ocean acidification conditions across California's diverse marine environments. Given that pH and/or $p\text{CO}_2$ of seawater are variable in many of California's marine ecosystems, carbonate chemistry time-series need to be of sufficient length and measurement frequency before trends beyond natural variability can be detected (Sutton et al., 2019). One of the two CCE moorings (CCE1) has been in operation long enough; CCE2 is expected to reach a sufficient record length for trend detection within the next five years. However, limitations to our ability to detect long-term trends in carbonate chemistry along California's coast include lapses in monitoring programs, due to funding limitations. Many other ocean acidification monitoring efforts do not yet have the frequency and length of observations to detect trends. Measurements of other carbonate chemistry variables (in order of preference: dissolved inorganic carbon, total alkalinity, pH), in addition to $p\text{CO}_2$, will allow additional insight into the changes associated with ocean acidification. Future expansion and extension of the current monitoring network for ocean acidification was a major recommendation of the West Coast Ocean Acidification and Hypoxia Panel (Chan et al., 2016), and the 2020–2029 Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020–2029 which calls for increased ocean acidification monitoring in important nearshore and subsurface habitats. Ideally, a robust future monitoring system integrating ocean acidification, hypoxia, and biological observations will enable tracking of changing ocean conditions under either accelerated or mitigated emissions and climate change scenarios.



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