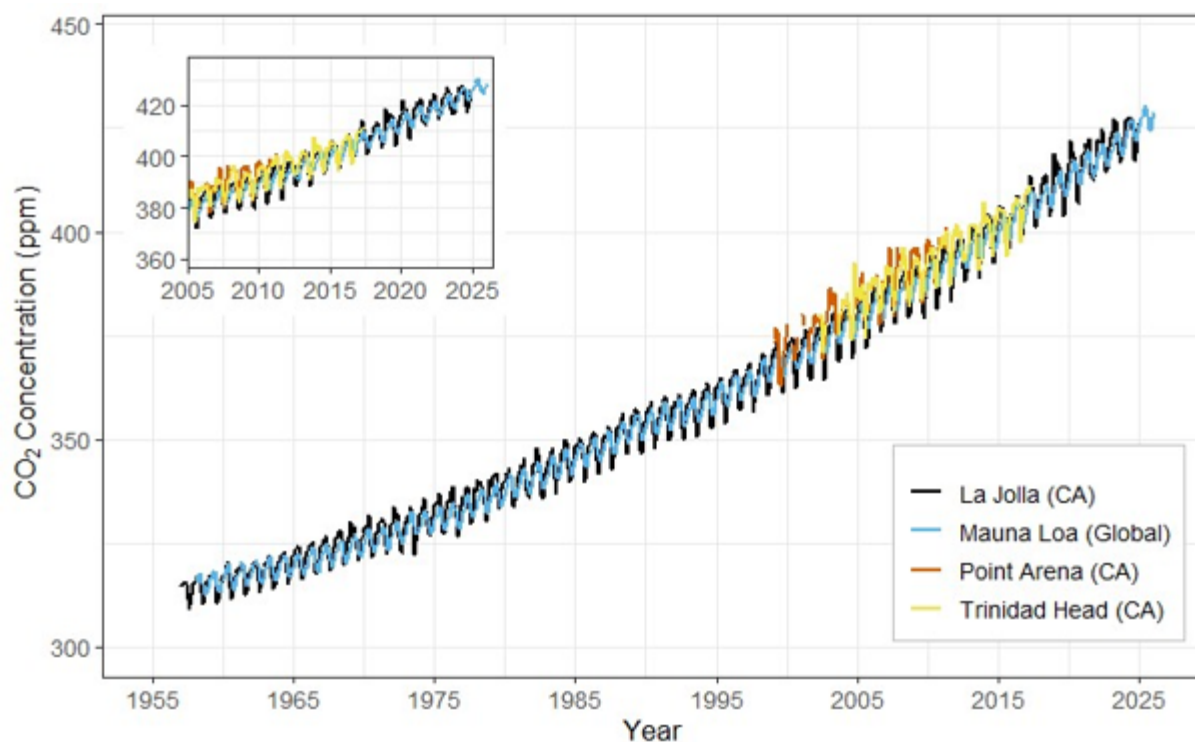


1.2 Atmospheric Greenhouse Gas Concentrations

Atmospheric concentrations of greenhouse gases such as carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and certain fluorinated gases (F-gases) continue to increase globally and in California. The annual global average concentrations of CO₂ were 417 parts per million (ppm) in 2022, 419 ppm in 2023, 423 ppm in 2024, and 426 ppm for 2025 (NOAA, 2026a).

Figure 1.2.1. Monthly Average Atmospheric CO₂ Concentrations.



This graph shows CO₂ measurements at Mauna Loa (1958-present), and three coastal sites in California: La Jolla, Point Arena (1999-2011), and Trinidad Head (2002-2017). Source: NOAA (2026a), and Conway et al. (2011) (Mauna Loa, Point Arena, and Trinidad Head); SIO (2025) (La Jolla)



What does the indicator show?

Atmospheric concentrations of greenhouse gases are increasing globally ([Figure 1.2.1](#) through [Figure 1.2.4](#)). The ambient concentrations of the following greenhouse gases at the global background site of Mauna Loa on the island of Hawaii, as well as at regional background sites in California, are presented:

- carbon dioxide (CO₂),
- methane (CH₄),
- nitrous oxide (N₂O),
- a variety of fluorinated gases (F-gases).

Measurements are displayed in parts per million (ppm) for CO₂, parts per billion (ppb) for CH₄ and N₂O, and parts per trillion (ppt) for F-gases. These are units of air pollution mixing ratios commonly used to describe ambient air pollution concentrations (1 ppm = 1,000 ppb = 1,000,000 ppt).

Carbon dioxide (CO₂)

Annual average CO₂ concentrations measured at Mauna Loa have increased from 315 ppm in 1958 to 426 ppm in 2025, at an average rate of approximately 1.6 ppm per year over the past few decades, accelerating in the last five years to about 2.5 ppm per year. As shown in [Figure 1.2.1](#), CO₂ exhibits a seasonal trend with increasing CO₂ levels observed from autumn through late winter and decreasing CO₂ levels from spring through late summer. This is due to seasonal biosphere-atmosphere interactions – that is, plants take up more CO₂ in spring and summer, then decay and release CO₂ in fall and winter along with subtle seasonal changes in anthropogenic fossil fuel use.

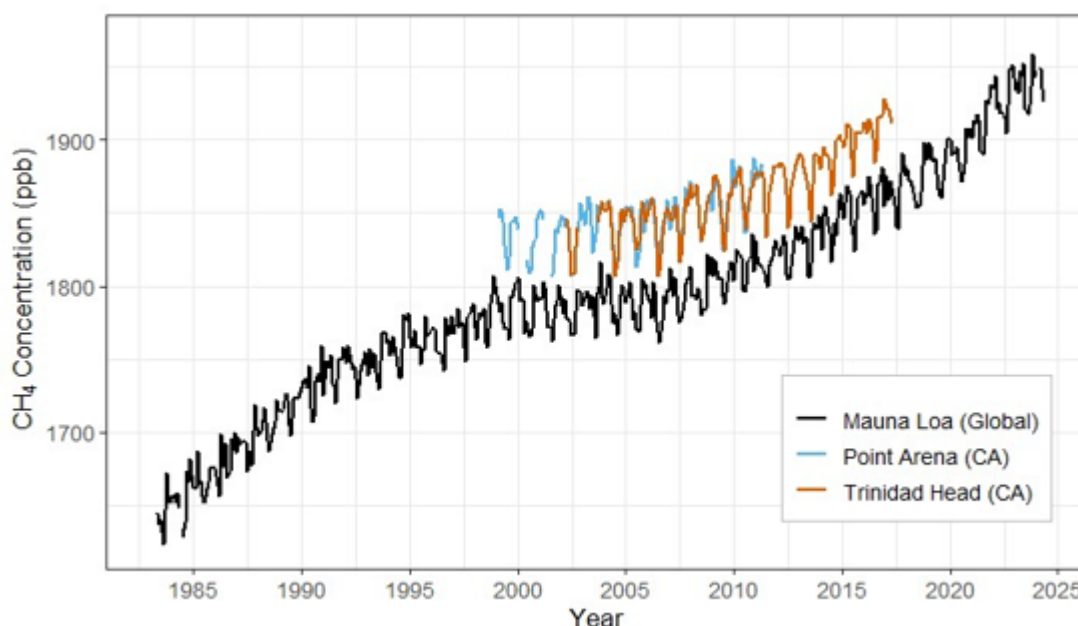
In the Northern Hemisphere, CO₂ concentrations tend to increase when moving north from the equator. This latitudinal gradient is largely a result of global population centers (and hence, sources of CO₂) being located at higher latitudes. As a result, CO₂ levels tend to be slightly higher at California sites than at Mauna Loa, and at northern California sites (Trinidad Head and Point Arena) than at La Jolla in southern California. California sites also tend to have higher variability than the Mauna Loa site, primarily due to their location on a major continent with large population centers and forested regions, which act as sources and sinks of CO₂, respectively.



Methane (CH₄)

Global CH₄ levels have increased since 1983, except for a brief period between 1999 and 2006 when they were relatively constant before increasing again starting in 2007. CH₄ concentrations in the pre-industrial era (i.e., pre-1750) were approximately 722 ppb (IPCC, 2013). By contrast, today's atmospheric CH₄ concentrations exceed 1900 ppb at Mauna Loa and the California sites – an increase of over 150% (**Figure 1.2.2**; NOAA, 2026b). Concentrations at the California sites are higher than those observed at Mauna Loa. As with CO₂, this is due to a strong latitudinal gradient that promotes elevated CH₄ concentrations in the northern latitudes, where more human activities lead to greater emissions (Frankenberg et al., 2005).

Figure 1.2.2. Monthly Average Atmospheric CH₄ Concentrations.



The graph shows CH₄ measurements at Mauna Loa (1983 to present), Point Arena (1999 to 2011), and Trinidad Head (2002 to 2017). Source: NOAA (2026b)

Regional sources of greenhouse gas emissions in California can lead to elevated concentrations above global background levels. Satellite data reveal significant subregional differences in CH₄ concentrations.



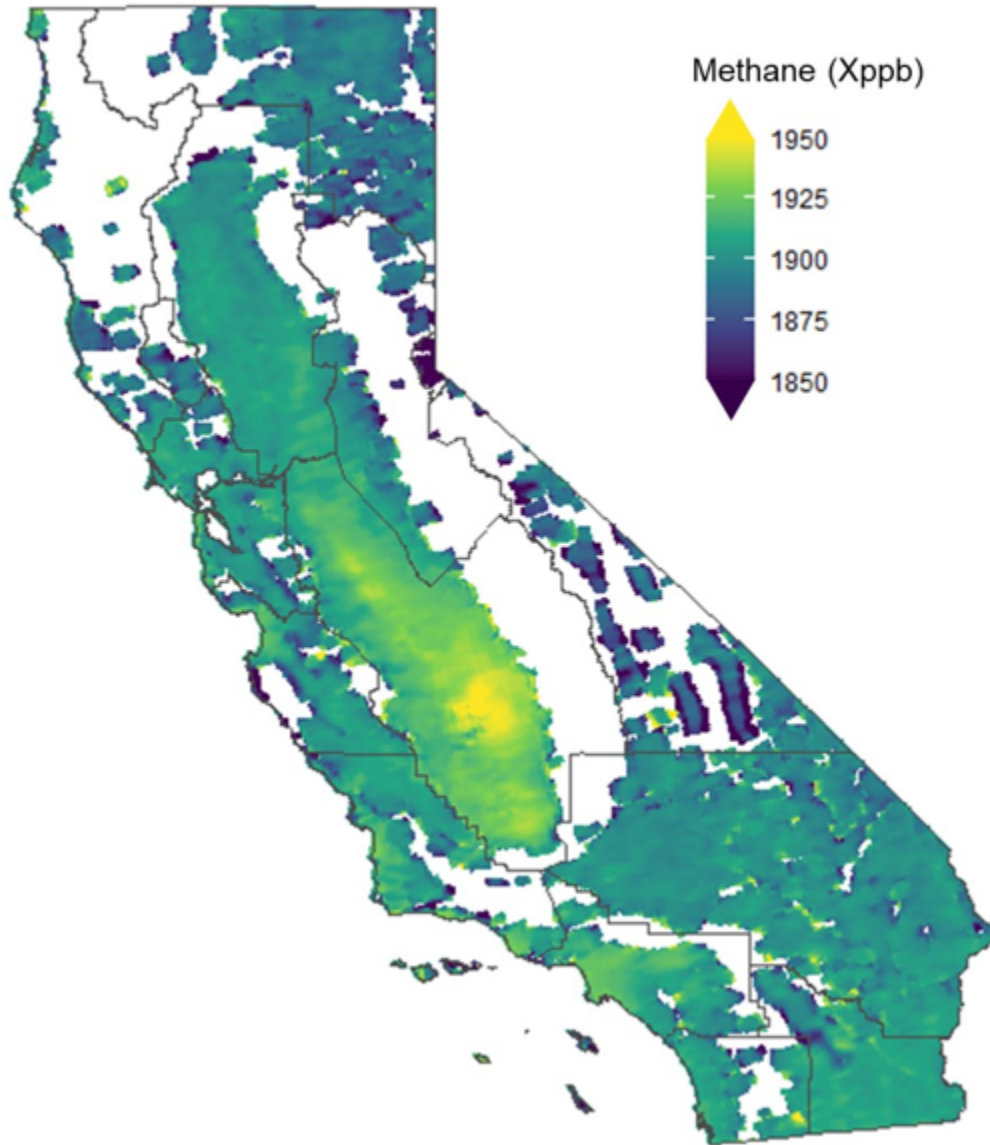
Figure 1.2.3 shows column-integrated CH₄ concentrations (Xppb) over California in 2023, measured by Tropospheric Monitoring Instrument (TROPOMI) (ESA, 2024). In addition to the monitoring and measurement efforts undertaken by various researchers, CARB has also funded several studies to utilize the atmospheric measurements from regional greenhouse gas monitoring sites to infer the most likely distribution and strength of regional CO₂, CH₄, and N₂O emission sources in California (Fischer and Jeong, 2016; Zhao et al., 2009; Cui et al., 2019). These top-down studies enhance understanding of California's methane emissions, supporting inventory findings that identify San Joaquin Valley as the largest regional contributor to the statewide methane emissions.

The following regions contribute the most to statewide CH₄ emissions (**Figure 1.2.4**; Jeong et al., 2016 and 2017; Cui et al., 2015 and 2019):

- San Joaquin Valley Air Basin: approximately 50% of total emissions, mainly from dairy farms and active oil and gas operations,
- South Coast Air Basin: about 20% of total emissions, primarily from oil and gas industries, landfills, and dairy farm operations,
- Sacramento Valley: about 10% of total emissions, primarily from agriculture and landfills,
- San Francisco Bay Area: nearly 10% of the state's total CH₄ emissions, primarily from landfills, dairy livestock and fossil fuel sources.



Figure 1.2.3. TROPOMI Satellite Observations of Methane over California in 2023*.

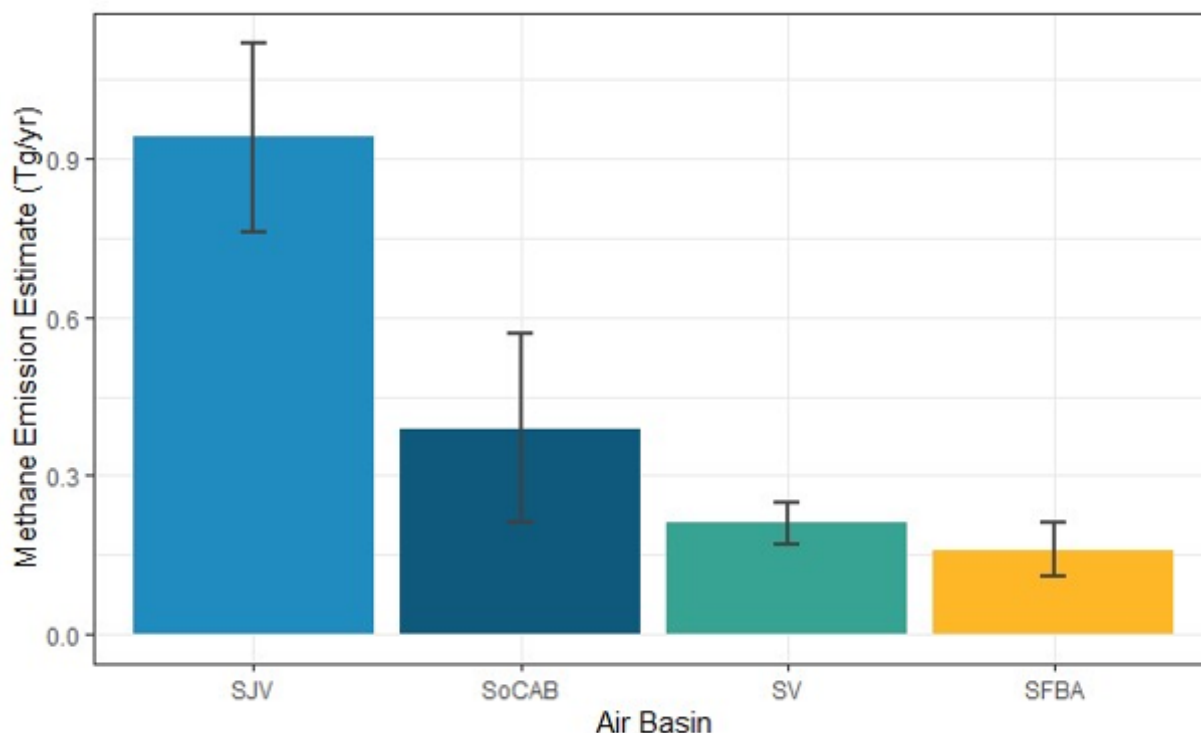


This figure shows TROPOMI satellite observations of methane over California in 2023. Methane is reported in Xppb, where “X” indicates a column-averaged mixing ratio rather than a surface value because the satellite measures the entire column of air from the sensor to the ground. Black lines designate air basin boundaries.

Source: ESA (2024)



Figure 1.2.4. Top-Down Regional Emission Estimates of Methane.

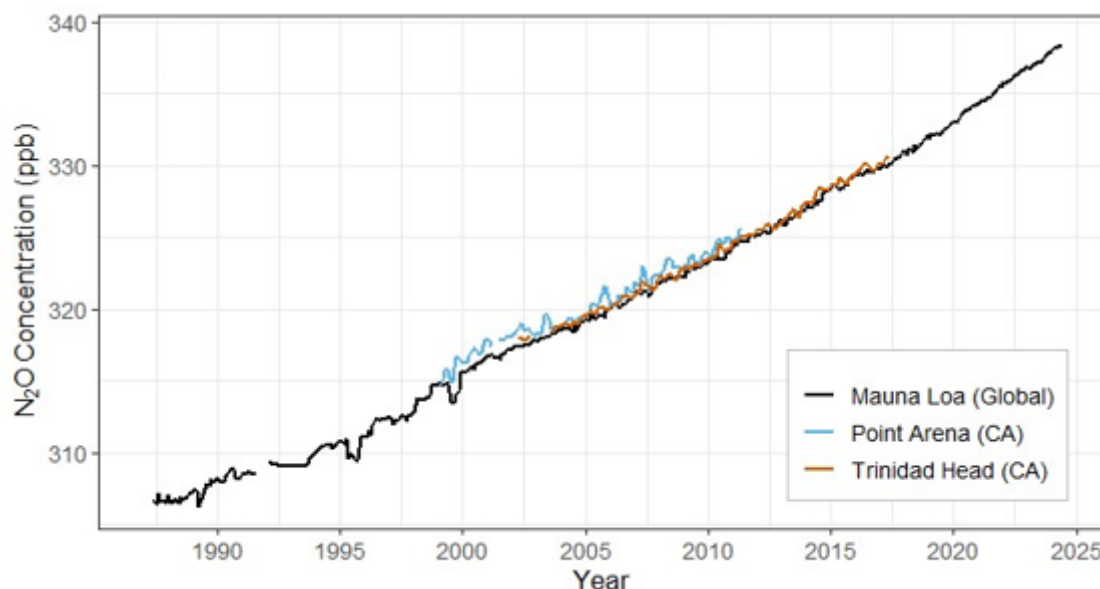


Methane emission estimates (Tg*/yr) for four major emission regions are presented below: San Joaquin Valley (SJV), Southern California Air Basin (SoCAB), Sacramento Valley (SV), and the San Francisco Bay Area (SFBA). *Teragram (Tg)=1 trillion grams=1 million metric tons; Source: Cui (2019)

Nitrous oxide (N₂O)

Global N₂O concentrations have been increasing at a rate of approximately 0.9 ppb per year over the past few decades (**Figure 1.2.5**). N₂O concentrations are now approximately 24% greater than the pre-industrial levels of 270 ppb (NOAA, 2026c). Global N₂O concentration trends do not display a strong seasonal cycle in the lower atmosphere.



Figure 1.2.5. Monthly Average N₂O Concentrations.

This graph shows the atmospheric concentrations of N₂O at Mauna Loa (1987 to present), Trinidad Head (2002 to 2017), and Point Arena (1999 to 2011). Source: NOAA (2026c)

Fluorinated gases (F-gases)

F-gases are potent greenhouse gases that can trap heat hundreds to thousands of times more effectively than CO₂ (i.e., they have a high global warming potential). They are entirely synthetic with no known natural sources. F-gases began to appear in the atmosphere in the 20th century, primarily because of their use as refrigerants, and in smaller amounts from aerosol propellants, foam blowing agents, fire suppressants, industrial solvents, and medical sterilants. Pre-industrial F-gas concentrations are assumed to be zero. Interest in atmospheric measurements of F-gases first began in the 1970s when they were linked to the destruction of stratospheric ozone (i.e., the “ozone hole”) (Molina and Rowland, 1974).

Chlorofluorocarbons (CFCs): CFCs are strongly ozone-depleting, and their production and use were halted in 1996 under the Montreal Protocol (UNEP, 2012). Consequently, global ambient concentrations have been slowly decreasing since the mid-1990s. Although no new emissions are expected, CFCs remain in the atmosphere for decades after they are released. CFCs are now well-mixed throughout the atmosphere, and



there is no latitudinal gradient in atmospheric concentrations. Thus, Mauna Loa and Trinidad Head have nearly identical CFC levels.

Hydrochlorofluorocarbons (HCFCs): HCFCs were an interim replacement for CFCs. While not as destructive towards stratospheric ozone as CFCs, HCFCs still have considerable ozone depletion potential and are also being phased out globally. Banned in the US and European Union, HCFC-22 still has limited use and production in developing countries. HCFC-22 has a latitudinal gradient that closely follows human population centers (i.e., higher levels in the mid-latitudes), thus levels are higher at Trinidad Head than at Mauna Loa. Ambient monitoring indicates an increasing HCFC-22 trend since the 1990s. Concentrations have begun to plateau in recent years as global phase-outs have ramped up.

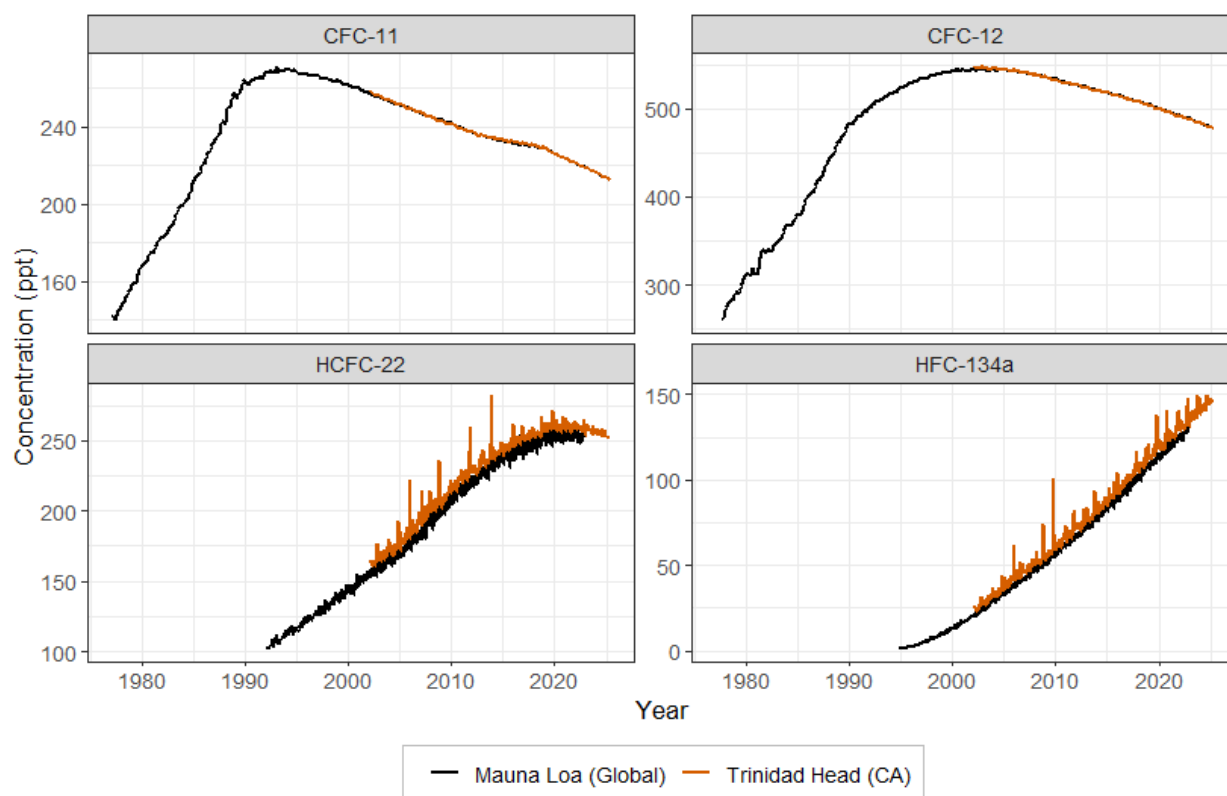
Hydrofluorocarbons (HFCs): HFCs are refrigerants. They have negligible ozone depletion potential and thus have been widely used across the world since their introduction in the mid-1990s, despite their high global warming potential. First detected in the atmosphere in the 1990s, concentrations of one prevalent HFC (HFC-134a) have risen, but others have plateaued or decreased. HFC-134a concentrations have grown at approximately 5 ppt per year since 2005. Like HCFCs, HFC-134a levels follow population centers and display a latitudinal trend, whereby Trinidad Head typically experiences higher levels than Mauna Loa.

Figure 1.2.6 shows the atmospheric concentrations at Mauna Loa and Trinidad Head of the four most prevalent F-gases:

- trichlorofluoromethane (CFC-11),
- dichlorodifluoromethane (CFC-12),
- chlorodifluoromethane (HCFC-22),
- 1,1,1,2-tetrafluoroethane (HFC-134a).



Figure 1.2.6. Monthly Average F-gas Concentrations.



The graphs show monthly average concentrations with individually scaled y-axes chosen to best highlight the unique trends and patterns of each gas. Source: NOAA (2026d)

Why is this indicator important?

Global temperatures are directly linked to greenhouse gas levels in the atmosphere (IPCC, 2021). Greenhouse gas emissions reduction targets have been established to prevent atmospheric concentrations from reaching levels that would result in irreversible, catastrophic impacts (see the *Greenhouse Gas Emissions* chapter).

The 2015 Paris Agreement aims to hold the increase in the global average temperature to below 3.6°F (2°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 2.7°F (1.5°C) above pre-industrial levels (UNFCCC, 2016). Atmospheric greenhouse gas concentrations help track changes in the emissions of anthropogenic drivers of climate change and their accumulation in, and removal from, the atmosphere.



Though all Californians are affected by climate change, disadvantaged communities often lack the financial resources to adapt to its effects and may therefore experience stronger negative impacts from extreme heat (see the *Extreme Heat Events* chapter), wildfire smoke (see the *Wildfire Smoke* chapter), and flooding (see the *Coastal Flooding* chapter). Due to structural and historical inequities, these communities may also face compounding vulnerabilities, including proximity to emission sources and reduced access to health. These factors can amplify health concerns in a warming climate (Casey et al., 2021; Lieb et al., 2025; Morello-Frosch and Obasogie, 2023).

CO₂ is a long-lived GHG responsible for approximately 65% of the total warming effect caused by greenhouse gases globally. It contributes about 80% of the current greenhouse gas emission inventory in California on a 100-year timescale (CARB, 2025a; WMO, 2016). CO₂ remains in the atmosphere for many centuries, so atmospheric levels may remain elevated for some time even if emissions are significantly reduced.

Additional atmospheric greenhouse gases amplify the warming driven by CO₂. CH₄ accounts for 25% of this added warming, while N₂O and F-gases together contribute less than 10% (IPCC, 2021; CARB, 2022). CH₄ and certain F-gases have a much shorter lifetime than that of CO₂ and are called “short-lived climate pollutants” (SLCPs). Even so, they could play a more important role in climate change than CO₂ owing to their greater 100-year global warming potentials as compared to that of CO₂.

The 100-year global warming potential is a standardized metric that compares the amount of heat trapped by a greenhouse gas over a 100-year period to the amount trapped by the same mass of CO₂ (CARB, 2025b). It allows scientists and policymakers to express the climate impact of different gases using a single, comparable value. CH₄ has a 100-year global warming potential of approximately 28 (i.e., 1 ton of CH₄ traps 28 times more heat over 100 years than 1 ton of CO₂) and remains in the atmosphere for about 12 years before removal, whereas F-gases such as HCFC-22 and HFC-134a have global warming potentials of over 1,000 and can remain in the atmosphere for one to two decades. On the other hand, N₂O has a 100-year global warming potential of 273 and remains in the atmosphere for approximately 120 years (IPCC, 2021).



What factors influence this indicator?

The concentrations of CO₂, CH₄, N₂O, and F-gases in the atmosphere reflect the difference between their rates of emission and their rates of removal. Many of the changes observed in global and regional greenhouse gas trends are directly related to human activities, including fossil fuel combustion, biomass burning, industrial processes, agricultural practices, and deforestation (IPCC, 2013). Additional discussion of factors affecting the emission of these greenhouse gases in California is presented in the *Greenhouse Gas Emissions* chapter.

CO₂

CO₂ is continuously exchanged between land, oceans, and the atmosphere through physical, chemical, and biological processes (IPCC, 2021). Prior to 1750, the global background CO₂ concentration was estimated to be less than 280 ppm (WMO, 2016). During this period, the amount of CO₂ released by natural processes (e.g., respiration and decomposition) was almost exactly in balance with the amount absorbed by plants during photosynthesis and other removal processes (WMO, 2016).

The increase in CO₂ concentration today primarily derives from emissions related to fossil fuel combustion and biomass burning. It is also directly related to changes in agricultural practices and deforestation (IPCC, 2021). While more than half of the emitted CO₂ is removed through natural processes within a century, approximately 20% remains in the atmosphere for many millennia (Archer et al., 2009). Consequently, atmospheric CO₂ concentrations may remain high for some time even if annual CO₂ emissions are substantially reduced from present levels.

While increasing levels of atmospheric CO₂ are affecting climate, changes in climate are likewise affecting the processes that lead to CO₂ uptake from, and release into, the atmosphere (IPCC, 2021). For example, warming temperatures increase plant photosynthesis, thereby enhancing CO₂ removal from the atmosphere, while wildfires release carbon that plants have stored back into the atmosphere (WMO, 2016).

Inter-annual variations have been attributed to El Niño and La Niña climate conditions; generally, higher-than-average increases in CO₂ correspond to El Niño conditions, and lower-than-average increases correspond to La Niña conditions (IPCC, 2021).



CH₄

Atmospheric CH₄ originates from both natural and anthropogenic sources. CH₄ is emitted naturally from the following:

- wetlands,
- oceans,
- termites,
- geological sources.

Anthropogenic sources of methane include:

- rice agriculture,
- livestock,
- landfills,
- waste treatment,
- biomass burning,
- fossil fuel and natural gas exploitation (i.e., extraction, transmission, distribution, and use).

The production of CH₄ by many of these sources is influenced by anaerobic fermentation processes and climate variables (notably temperature and moisture). Atmospheric removal of CH₄, on the other hand, is driven by oxidation processes, a process likewise affected by climate variables.

N₂O

Atmospheric N₂O is naturally present in the atmosphere as part of the Earth's nitrogen cycle. Its primary driver is the breakdown of nitrogen by microorganisms that live in soil and water (Anderson et al., 2010). N₂O is removed from the atmosphere through bacterial activities and through photochemical reactions (US EPA, 2024).

Human activities, including agriculture, fossil fuel combustion, wastewater management, and industrial processes, account for approximately 40% of total N₂O emissions globally (US EPA, 2024). In California, agricultural activities such as soil and manure management contributed approximately 55% of statewide N₂O emissions in 2023, with the remaining 45% primarily from transportation, industrial, commercial, and residential



sectors (CARB, 2025a). Synthetic fertilizers are a significant source of N_2O , as are tailpipe emissions from motor vehicles with inefficient engines and catalytic converters.

F-gases

As previously mentioned, F-gases do not exist in the natural environment; they are only emitted from anthropogenic sources and are only removed through photochemical reactions in the upper atmosphere. F-gases have been used primarily as refrigerants in a variety of applications, including:

- stationary refrigeration and air conditioning,
- industrial production and manufacturing processes,
- transmission and distribution of electricity, and
- vehicle air conditioning systems.

CFC-11, CFC-12, HCFC-22, and HFC-134a emissions derive largely from the following sources (Gallagher et al., 2014):

- fugitive leaks,
- venting during the maintenance and servicing of equipment,
- leaks from improperly maintained or damaged equipment, and
- improper disposal of equipment.

International, national, and state regulations affect the use, emission, and eventual atmospheric concentrations of F-gases. As noted above, pursuant to the Montreal Protocol of 1987, CFCs were phased out and banned in the United States in 1996. Most HCFCs were phased out of new production and consumption as of January 1, 2020.

Driven by the phase-out of ozone-depleting substances and by increased demand for refrigeration and air conditioning, HFCs became the fastest-growing source of greenhouse gas emissions in California and globally. Most HFC emissions in California come from refrigerants (CARB, 2025a). Prior to ratification of the Kigali Amendment, the U.S. Congress enacted the American Innovation and Manufacturing (AIM) Act of 2020, which directs the U.S. Environmental Protection Agency (US EPA) to:

- phase down the production and consumption of listed HFCs and their substitutes,
- facilitate the transition to next-generation technologies.



The U.S. EPA has adopted several rules to achieve the goals of the AIM Act. The following measures are already in place in California:

- California Senate Bill 1383 (Statutes of 2016): requires statewide reduction of HFC emissions to 40% below 2013 levels by 2030 (CARB, 2017).
- California Senate Bill 1013 and CARB regulation: Prohibits HFCs with high global warming potential in certain stationary refrigeration and foam end uses and establishes the F-gas Reduction Incentive Program to increase adoption of climate-friendly refrigerant technologies.

Several other states followed California by adopting similar rules in their respective jurisdictions, including Connecticut, Delaware, Maryland, and New York. In December 2020, CARB approved additional HFC measures (previously identified in CARB's Short-Lived Climate Pollutant Strategy), including:

- Global warming potential limits on new and existing refrigeration and air-conditioning equipment,
- Company-wide reduction targets for retail food refrigeration facilities,
- Refrigerant Recovery Reclaim and Reuse or the R4 Program: a first of its kind program requiring the use of reclaimed refrigerant in air conditioning equipment.

More recently, California adopted SB 1206, which mandates the following:

- Prohibits the sale of newly produced HFCs with high global warming potentials on a phased-in timeline, ending with HFCs that have a GWP greater than 750 in 2033.
- Requires the use of reclaimed HFCs instead of high-GWP HFCs to promote recovery and better management of HFCs from existing equipment and prevent their release into the environment.
- Release of an assessment report (expected to be published on July 1, 2025) by CARB in collaboration with the California Energy Commission on how to transition the state's economy, by sector, away from HFCs and to ultra-low-GWP (GWP < 10) or no-GWP alternatives no later than 2035 and how to maximize recovery and reclamation of HFCs.



California continues to evaluate further HFC reduction measures that will be needed to meet the SB 1383 target and long-term carbon neutrality goals.

Technical considerations

Data characteristics

The CO₂ data in [Figure 1.2.1](#) combines measurements from the Scripps Institution of Oceanography (SIO) and the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA-ESRL). NOAA-ESRL leads the Carbon Cycle Cooperative Global Air Sampling Network, which collects discrete air samples from observatories, cooperative fixed sites, and commercial ships (NOAA, 2026e). Weekly glass flask samples are analyzed using non-dispersive infrared absorption (Keeling et al., 2001), while at SIO's La Jolla Pier, monthly samples are collected. Ambient CH₄, N₂O, and F-gas concentrations ([Figure 1.2.2](#), [Figure 1.2.5](#), and [Figure 1.2.6](#)) were also obtained from the NOAA-ESRL networks. NOAA-ESRL collected samples in evacuated flasks and detected CH₄ using a flame ionization detector integrated with a gas chromatograph system, *in situ* systems to measure N₂O, and an electron-capture detector and a mass spectrometer to measure F-gases.

Satellite data of atmospheric CH₄ is presented in [Figure 1.2.3](#) as column-average concentrations from the surface to the top of the atmosphere. Atmospheric inverse modeling, presented in [Figure 1.2.4](#), used computer models to trace CH₄ emissions to their sources, providing valuable insights into when and where emissions occurred. The inverse modeling was driven by data collected from the CARB Statewide GHG Monitoring Network, the Megacities Carbon Project's tower sites in the Los Angeles area, and NASA's Alpha Jet Atmospheric eXperiment, which flew missions over the San Francisco Bay Area and northern San Joaquin Valley (Cui et al., 2019).

Strengths and limitations of the data

Long-term, high-precision measurements presented in this chapter are essential for understanding greenhouse gas emissions from various sources – including human activities, atmospheric processes, plants, soils, and oceans. Tracking the life cycles of these greenhouse gases provides crucial information for formulating effective mitigation strategies. Data on atmospheric greenhouse gas levels are needed to project future



climate change associated with various emission scenarios, and to establish and revise emission reduction targets (IPCC, 2013).

Measurement data from NOAA-ESRL undergo critical evaluation for quality control (NOAA, 2026f). The long-term record at La Jolla, particularly when compared with the longer-term data at Mauna Loa, presents valuable time-series information for tracking greenhouse gas trends over the past half century (SIO, 2025). These data are useful for characterizing seasonal variations and provide information about the coastal air that travels into California. Although the La Jolla Pier at SIO extends considerably into the ocean, the site can receive some air currents polluted with urban greenhouse gas emissions from the Los Angeles area that mix with the oceanic and San Diego atmosphere. Likewise, the Point Arena location, although coastal, occasionally captures onshore GHG emissions. The Trinidad Head monitor sits on a peninsula extending into the ocean with a tower, however, the air coming from the Pacific Ocean can back up on the nearby coastal range mountains and backflow to the site, thus impacting the measurements of GHG in the onshore air.

Inverse modeling provides atmospheric-based estimates that offer a high-level statewide emission assessment, track greenhouse gas trends over time as regulations are implemented and guide further research. Satellites may enhance these capabilities in the future. This approach relies on atmospheric concentration measurements from a limited number of sites across the state, covering key areas with major anthropogenic emissions. However, inverse studies have inherent uncertainties due to measurement limitations, inventory estimates, and gridding processes. Additionally, models introduce uncertainties when converting concentration data into emission estimates. The method also depends on a statewide inventory that must be disaggregated using additional assumptions.



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