

The Earth's climate is a complex, interactive system consisting of the atmosphere, land surfaces, water bodies, snow and ice, and living organisms. This system is influenced by its internal dynamics and by external factors, both natural and human-induced. Examples of natural factors include solar radiation and volcanic eruptions. Human-induced factors include fossil fuel combustion and deforestation (IPCC, 2021). The Earth has experienced natural cycles of climatic changes throughout its history. However, the current warming trend is unusual in that it is happening at an unprecedented rate due to human activity.

Heat-trapping greenhouse gases are the major human-influenced drivers of climate change, with carbon dioxide (CO<sub>2</sub>) being the largest contributor. Primarily emitted from fossil fuels, annual average global concentrations of CO<sub>2</sub> exceeded 400 parts per million (ppm) in 2015 for the first time since records began. This benchmark provides a stark reminder that atmospheric greenhouse gases continue to increase. Moreover, given that CO<sub>2</sub> persists in the atmosphere, levels will likely stay above 400 ppm for generations to come (IPCC, 2021).

California showed its commitment to limiting greenhouse gas emissions when it enacted the California Global Warming Solutions Act of 2006 (also known as AB 32). The law established the nation's first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective emissions reductions. California reached its target of reducing greenhouse gas emissions to 1990 levels by 2020, four years ahead of schedule, and emissions continue to decline, as an indicator in this section illustrates. Through further actions California aims to achieve carbon neutrality by 2045. This means that all greenhouse gas emissions are balanced by their removal from the atmosphere, either through carbon sinks or carbon capture and storage. The main natural carbon sinks are soil, forests and oceans.

Since the mid-1980s the ocean has absorbed approximately 20 to 30 percent of the CO<sub>2</sub> released into the atmosphere by human activities. While this has significantly slowed CO<sub>2</sub> buildup in the atmosphere, it has changed the chemistry of seawater (Bindoff et al., 2019; Canadell, et al., 2021; Friedlingstein et al., 2022). This change – called ocean acidification – is observed in California waters, and threatens the state's marine ecosystems, impacting some of the most ecologically and economically important species.

Other greenhouse gases include methane, nitrous oxide, and fluorinated gases such as hydrofluorocarbons and perfluorocarbons. Methane, hydrofluorocarbons, and



anthropogenic black carbon are more powerful warming agents than CO<sub>2</sub>, and have significantly shorter lifetimes in the atmosphere. Reducing emissions of these “short-lived climate pollutants” can have more immediate effects in slowing the rate of warming. California has a comprehensive strategy to reduce short-lived climate pollutants, and trends for certain pollutants show significant reductions.

International climate agreements aim to prevent “dangerous anthropogenic interference with the climate system.” The 2015 Paris Agreement commits to efforts to limit the global temperature increase to 1.5°C (2.7°F) (UNFCCC, 2016). There are [options available now](#) to do so and at least halve global emissions by 2030, including the use of renewable energy, which has become more cost-efficient and helped slow the growth rate of global emissions.

### INDICATORS: CLIMATE CHANGE DRIVERS

Greenhouse gas emissions (*updated*)  
Atmospheric greenhouse gas concentrations (*updated*)  
Atmospheric black carbon concentrations (*no update*)  
Acidification of coastal waters (*updated*)

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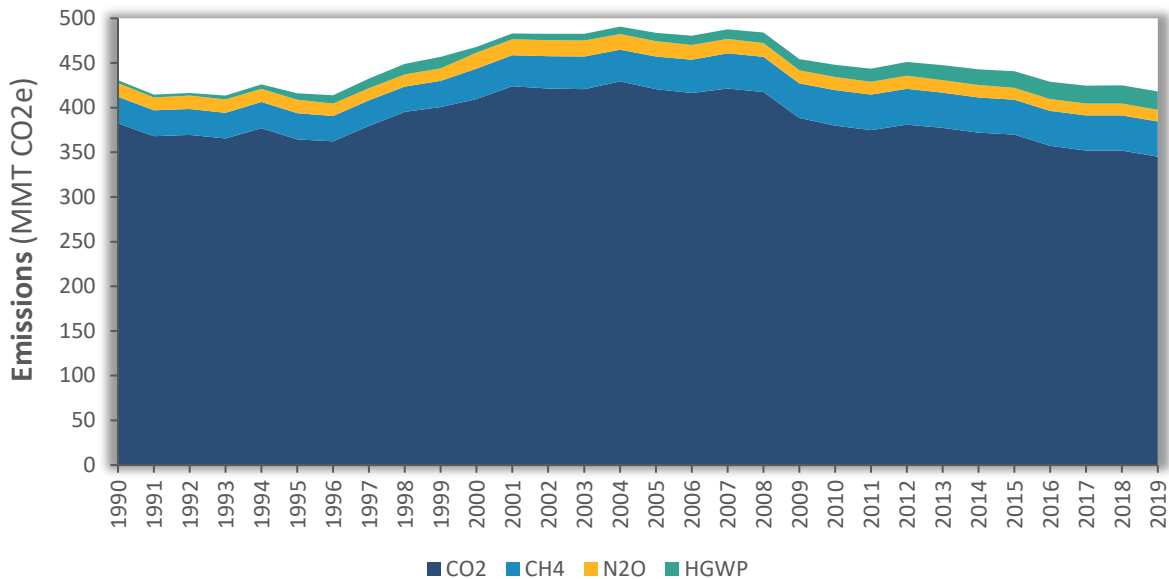
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## GREENHOUSE GAS EMISSIONS<sup>1</sup>

Statewide greenhouse gas (GHG) emissions peaked in 2004, but have since been on an overall downward trajectory. Emissions have remained below California’s GHG emissions reduction goal (431 million metric tons of carbon dioxide equivalent) since 2016. Similarly, GHG emissions have steadily decreased on a per capita and gross state product basis.

Figure 1. Greenhouse gas emissions in California 1990 - 2019, disaggregated by pollutant\*



Source: CARB, 2007; CARB, 2021a

\*Based on IPCC Fourth Assessment Report 100-year global warming potentials  
**MMTCO<sub>2</sub>e** = million metric tons of carbon dioxide equivalents

### What does the indicator show?

California’s combined emissions of the greenhouse gases (GHG) carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and high global warming potential (high-GWP) gases reached peak levels in 2004, but have since decreased and remained below the 1990 emissions levels since 2016 (CARB, 2021a). GHG emissions are expressed in million metric tons (MMT) of

### What are “CO<sub>2</sub> equivalents”?

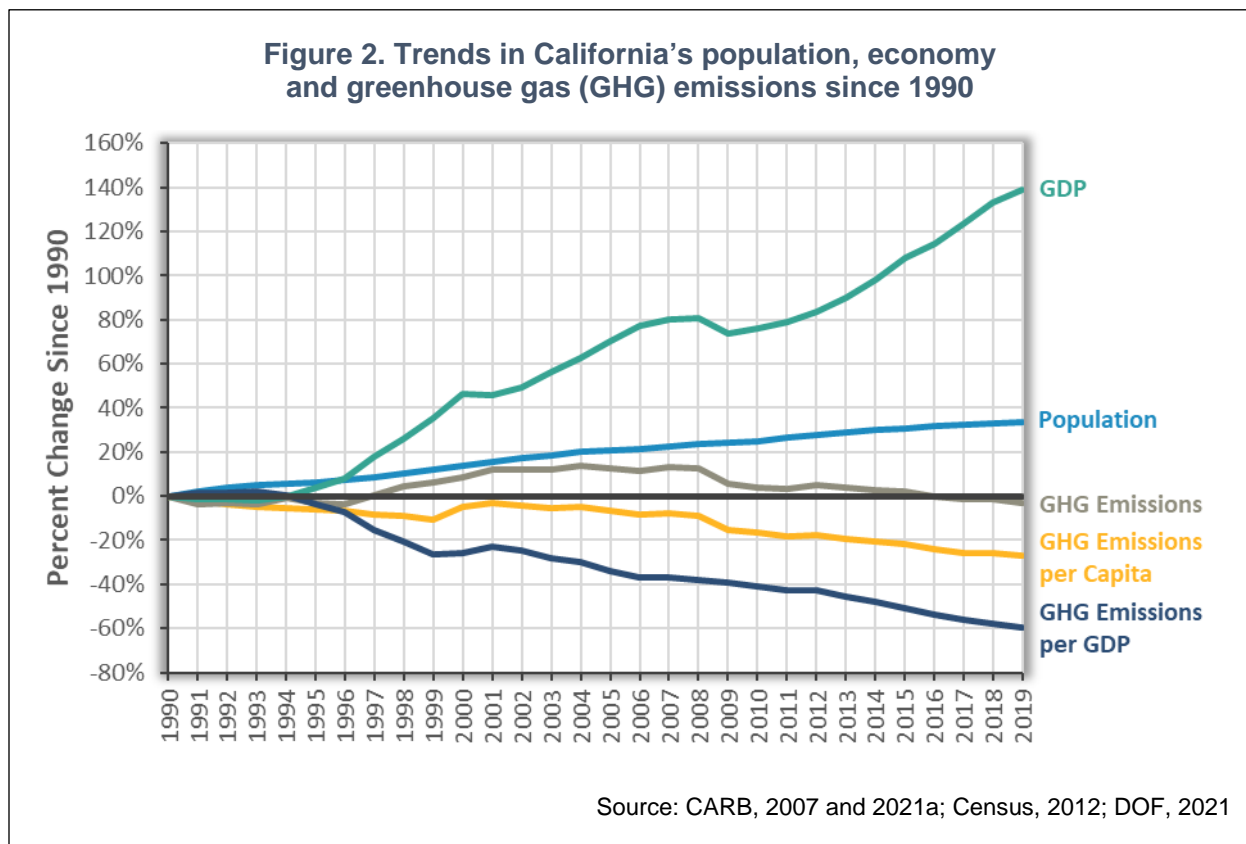
Emissions of greenhouse gases other than carbon dioxide (CO<sub>2</sub>) are converted to **carbon dioxide equivalents**, or **CO<sub>2</sub>e**, based on their global warming potential (GWP). GWP represents the warming influence of different greenhouse gases relative to CO<sub>2</sub> over a given time period and allows the calculation of a single consistent emission unit, CO<sub>2</sub>e.

<sup>1</sup> A new edition of the California Greenhouse Gas Inventory has since been released and includes data through 2020. The inventory is available at the [California Air Resources Board’s website](https://www.arb.ca.gov/ghg/).



100-year global warming potential values as specified in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2006).

CO<sub>2</sub> accounts for the largest proportion of GHG emissions, making up 83 percent of total emissions in 2019. In comparison, CH<sub>4</sub> and N<sub>2</sub>O account for 9 percent and 3 percent of total GHG emissions, respectively. The remaining 5 percent of GHG emissions consist of high-GWP gases including hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF<sub>6</sub>), and nitrogen trifluoride (NF<sub>3</sub>). Among these GHGs, methane and a subset of HFCs<sup>1</sup> are also considered short-lived climate pollutants (SLCPs), which are powerful climate forcers that remain in the atmosphere for a much shorter period than longer-lived climate pollutants such as CO<sub>2</sub>. SLCPs are discussed further below (see *Why is this indicator important?*).



GHG emissions per person (per capita) and per dollar of gross domestic product (GDP, a measure of the state’s economic output) show declining trends between 1990 and 2019 (Figure 2). During the same period, the state’s population and GDP increased by 33 percent and 139 percent, respectively. California’s 2019 GHG emissions are 3 percent lower than in 1990, but emissions per capita have declined by over 25 percent

<sup>1</sup> These include HFC-152a, HFC-32, HFC-245fa, HFC-365mfc, HFC-134a, HFC-43-10mee, HFC-125, HFC-227ea, and HFC-143a.



and emissions per dollar of GDP (carbon intensity) have declined by almost 60 percent. Total GHG emissions have also decreased from the peak in 2004 by 15 percent. A combination of factors contributed to this decrease in carbon intensity of the California economy. These factors include incrementally higher energy efficiency standards, growths in renewable energy sources, carbon pricing from the Cap-and-Trade Program, improved vehicle fuel efficiency, and other regulations.

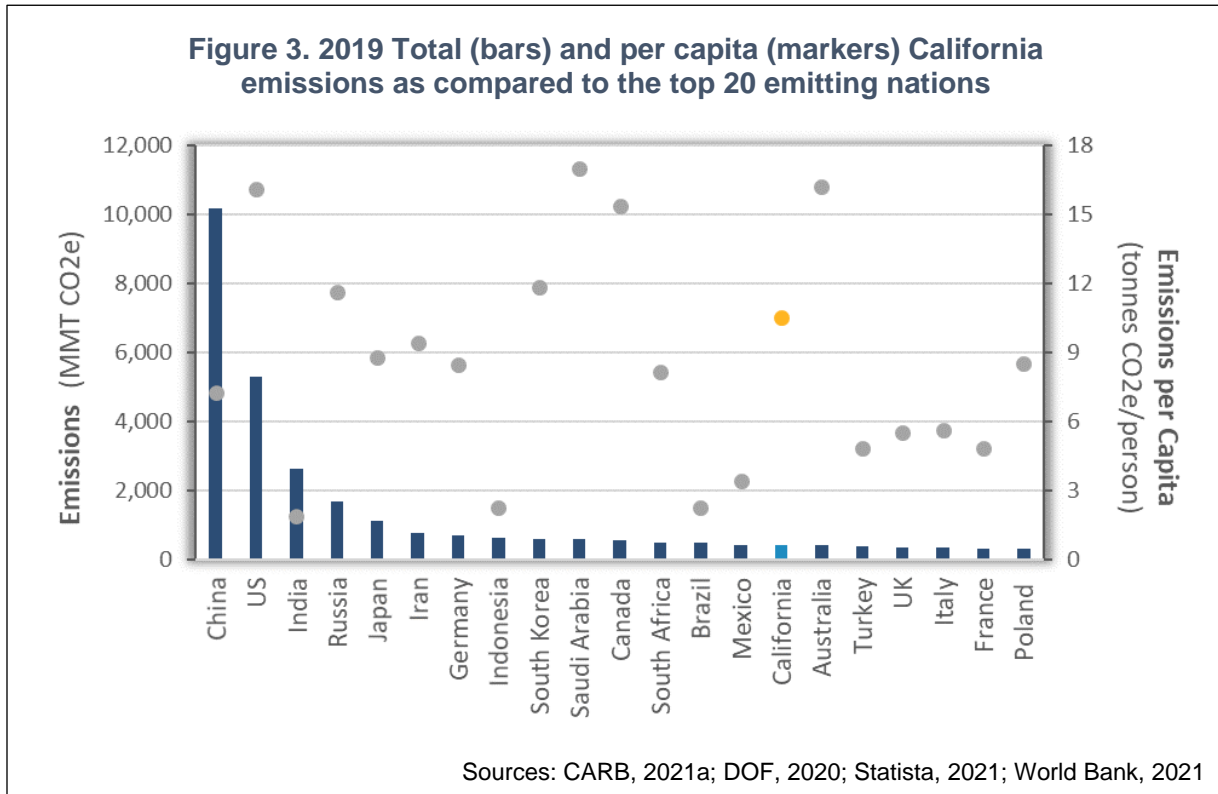
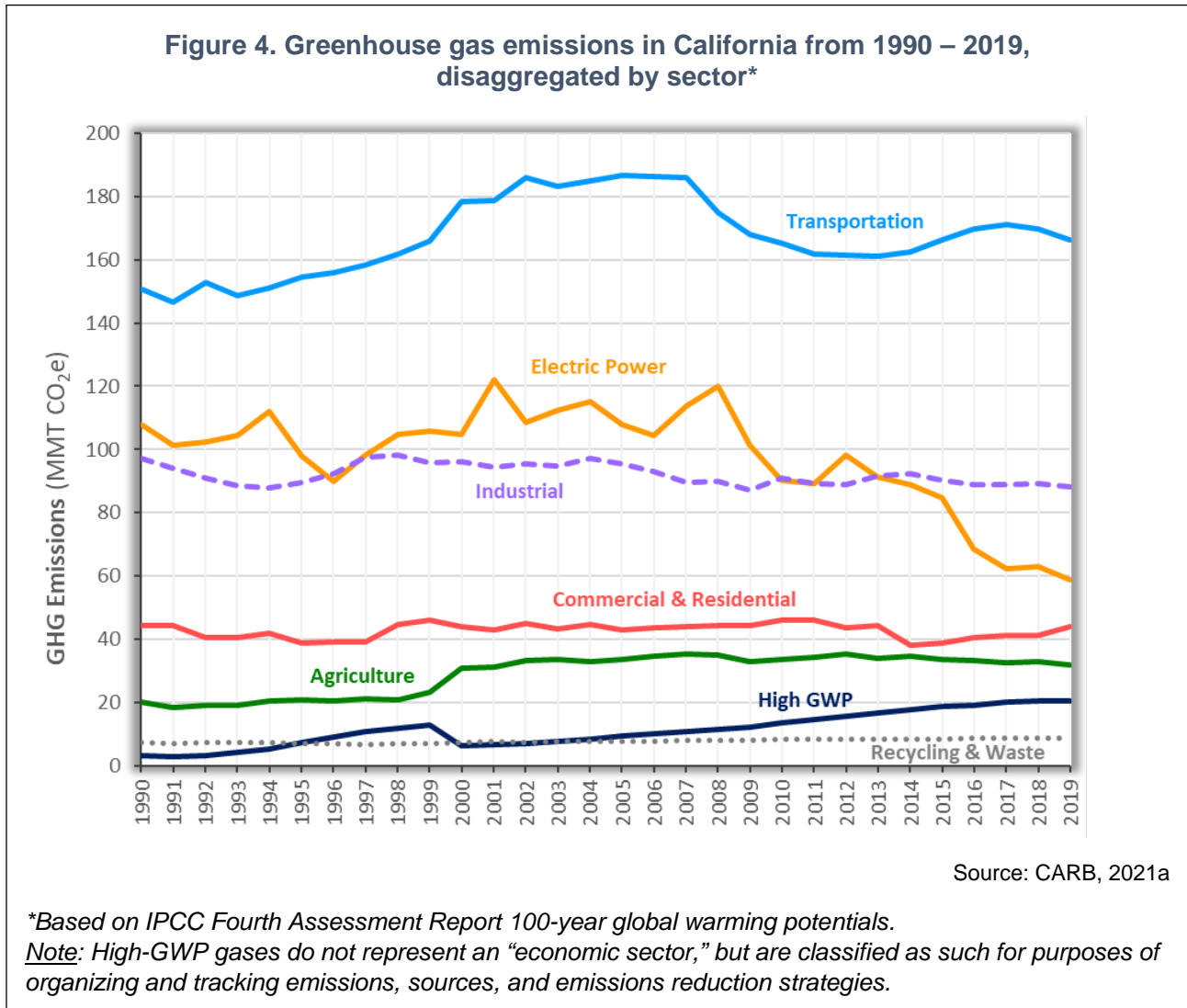


Figure 3 shows 2019 total emissions and emissions per capita for California compared to the top 20 emitting nations. If California were a country, it would be the fifth largest economy in the world. It would have the 15<sup>th</sup> highest total emissions, and the 7<sup>th</sup> highest per capita emissions. The state’s 2019 per capita emissions are 35 percent lower than those of the United States (CARB, 2021a, Statista, 2021, World Bank 2021).

Figure 4 shows GHG emissions from 1990 to 2019, organized by categories as defined in the California Air Resources Board’s (CARB) *Scoping Plan* (CARB, 2008). The transportation sector and the electric power sector are the primary drivers of year-to-year changes in statewide emissions. Transportation sector emissions increased between 1990 and 2007, followed by a period of steady decrease through 2013, and have followed a generally declining trend since. Most recently, total transportation emissions have steadily decreased from 2017 through 2019 due to a significant increase in biodiesel and renewable diesel use, which now accounts for 27 percent of total on-road diesel sold in California. Emissions from the electric power sector are variable over time but have decreased by more than 50 percent between 2008 and



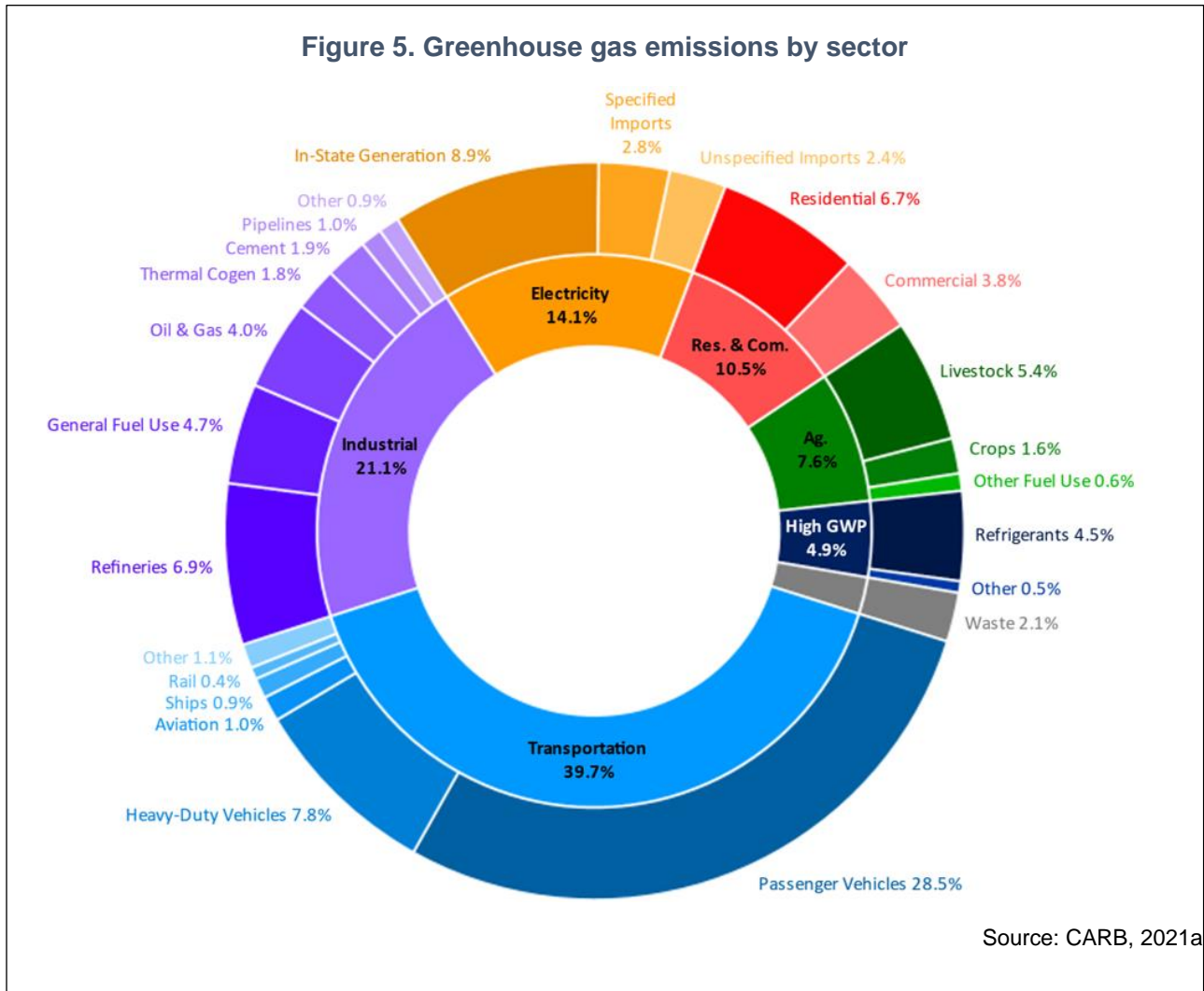
2019 due to a continuing increase in renewable energy. High-GWP gases make up a small portion of total emissions but are steadily increasing as they replace ozone-depleting substances that are being phased out under international accord (UNEP, 2016). Emissions from the other sectors show some year-to-year variations, but their trends are relatively flat over time.



Transportation is the largest source of GHGs, accounting for 39.7 percent of the total emissions in 2019 (Figure 5). Cars, light duty trucks, and sport utility vehicles constitute the highest contribution to transportation emissions. Industrial activities account for 21.1 percent of emissions and include fossil fuel combustion and fugitive emissions from a wide variety of activities such as manufacturing, oil and gas extraction, petroleum refining, and natural gas pipeline leaks. The electricity sector (in-state generation and electricity imports) accounts for 14.1 percent of emissions, followed by residential and commercial sources, which collectively account for 10.5 percent. The commercial sector, which includes schools, health care services, retail, and wholesale, accounts for



3.8 percent. The residential sector, where home natural gas use makes up the majority of emissions, accounts for 6.7 percent of statewide emissions. Emissions from the agricultural sector, which come from livestock, crop production, and fuel combustion, contributed 7.6 percent; these are mostly comprised of emissions from livestock. High-GWP gases are primarily used in refrigeration and air conditioning, as well as foams and consumer products and comprised 4.9 percent of 2019 emissions. Recycling and waste was the smallest contributor at 2.1 percent and includes emissions from landfills, wastewater treatment, and compost.



**Why is this indicator important?**

Atmospheric concentrations of GHGs have increased since the Industrial Revolution, enhancing the heat-trapping capacity of the earth's atmosphere. Accurately tracking GHG emissions trends in California provides critical information to policymakers as they assess climate change mitigation options and track the progress of GHG emissions reduction programs.

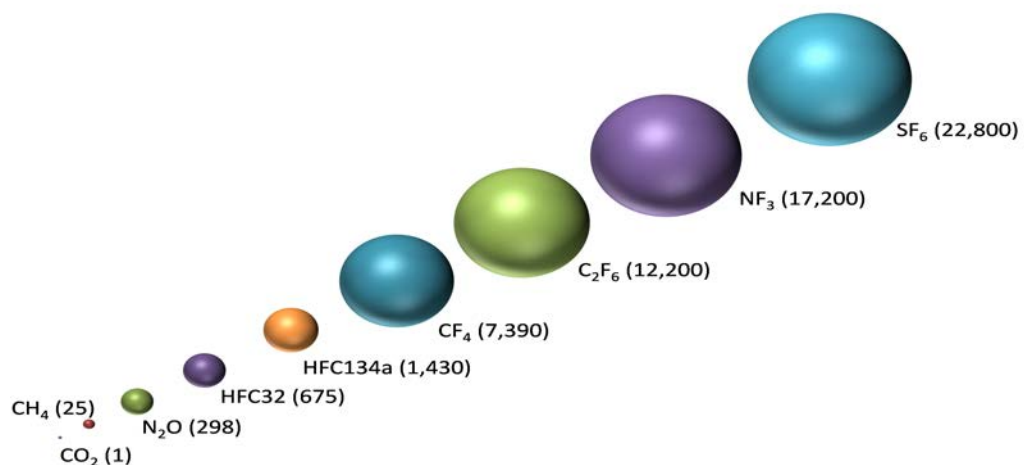


GHG emissions reduction targets are intended to prevent atmospheric concentrations from reaching levels at which catastrophic and irreversible impacts occur. The 2015 Paris Agreement aims to hold the increase in the global average temperature to well below 2 degrees Celsius (°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C above pre-industrial levels (UNFCCC, 2016). These efforts would significantly reduce the risks and impacts of climate change (Xu and Ramanathan, 2017). However, if global emissions continue to increase at the current rate, global warming is likely to reach 1.5°C between 2030 and 2052 (IPCC, 2018).

Since each GHG absorbs energy and warms the atmosphere to a different degree, understanding the pollutants' relative effects on climate change is also important for setting priorities and meeting emission reduction goals. Current international and national GHG inventory practice, as defined by the IPCC Guidelines, uses 100 years as the standard timeframe for GHG inventories. (Other timeframes may be used for different purposes. For example, discussions related to SLCPs typically use the 20-year timeframe.)

As illustrated in Figure 6, in a 100-year timeframe, CO<sub>2</sub> has the lowest GWP of all GHGs reported in the statewide inventory on a per unit of mass basis. Non-CO<sub>2</sub> emissions are converted to CO<sub>2</sub> equivalents (CO<sub>2</sub>e) using GWP. GWP is a measure of the extent to which a particular GHG can alter the heat balance of the earth relative to carbon dioxide over a specified timeframe. For example, the GWP of SF<sub>6</sub> is 22,800, meaning that one gram of SF<sub>6</sub> has the same warming effect as 22,800 grams of CO<sub>2</sub>.

**Figure 6. 100-Year global warming potential of greenhouse gases based on the IPCC Fourth Assessment Report**



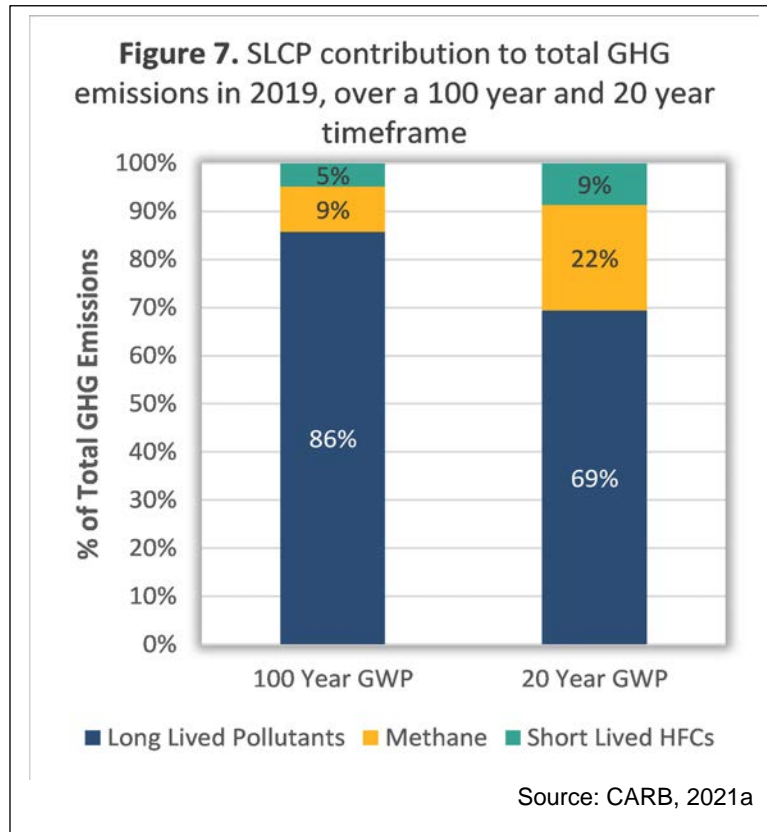
Source: IPCC, 2007





Emissions of CO<sub>2</sub>, the main contributor to climate change, stay in the atmosphere for hundreds of years. Reducing CO<sub>2</sub> emissions is critically important but will not result in near-term cooling because of this long residence time. In contrast to CO<sub>2</sub>, because SLCPs remain in the atmosphere from days to decades, a reduction in these emissions can have a more immediate impact, slowing the rate of warming.

Because SLCPs do not persist in the atmosphere for longer than decades, it is useful to consider a 20-year timeframe when discussing their impacts on climate change and planning for mitigation measures. Figure 7 shows the contribution of SLCP emissions to total GHG emissions in 2019. This contribution is based on their GWP and their atmospheric lifetime. Emissions of short-lived HFCs and methane in 2019 account for 14 percent of the total GHG emissions in a 100-year timeframe; however, when considering a 20-year timeframe, they account for 31 percent. In addition to methane and short-lived HFCs, black carbon, a class of particulate matter, is also considered an SLCP (see *Atmospheric black carbon concentrations* indicator).



**What factors influence this indicator?**

Statewide GHG emissions reflect activities across all major economic sectors, which are influenced by a variety of factors including population growth, vehicle miles traveled, economic conditions, energy prices, consumer behavior, technological changes, drought, and regulations, among other things.

Because GHG emissions from each sector are simultaneously influenced by multiple factors, one-to-one attribution between each factor and the magnitude of changes to sector emissions can be difficult to quantify. For example, improved economic conditions can result in an increased number of motor vehicles per household, and can boost vehicle miles traveled thus increasing GHG emissions, while using more fuel-efficient vehicles, public transportation, or driving less can reduce emissions.



GHGs are emitted from a variety of sources, but most notably from the combustion of fossil fuels used in the industrial, commercial, residential, and transportation sectors. GHG emissions also occur from non-combustion activities at landfills, wastewater treatment facilities, and certain agricultural operations. A discussion of trends in certain economic sectors, sources of SLCPs, and the influence of regulatory requirements is presented in the following sections. Further information is provided in CARB (2021b).

### Transportation

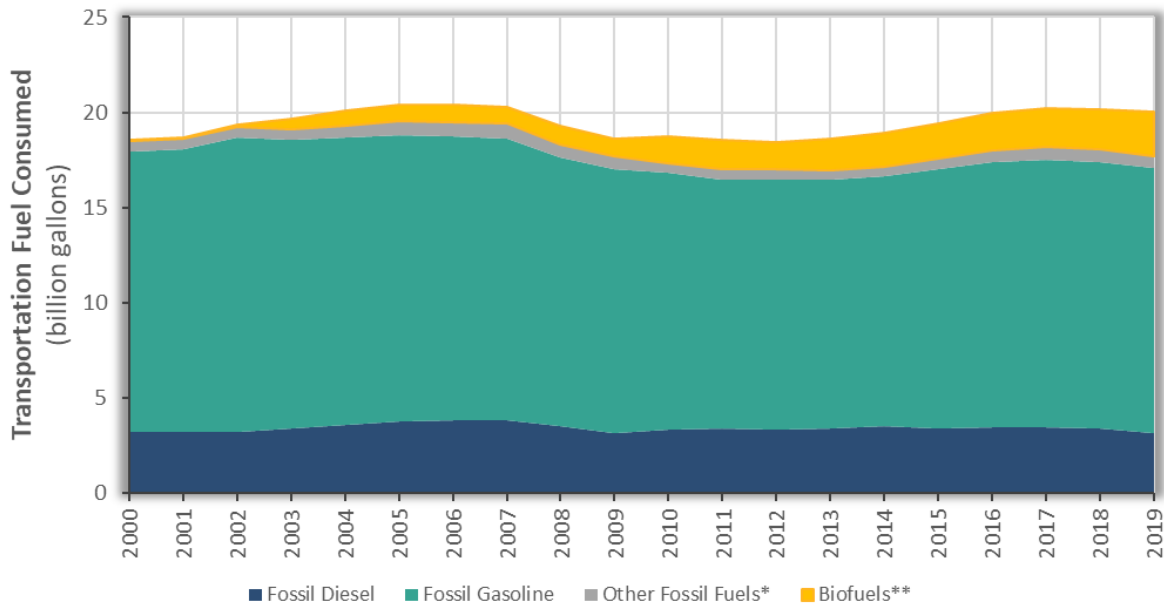
Although California's population has grown by 33 percent since 1990 (Figure 2), GHG emissions from the transportation sector have increased by only 10 percent (Figure 4). Furthermore, transportation emissions in 2019 were 11 percent lower than the peak level in 2005. The decrease in transportation GHG intensity per capita is largely due to a significant increase in biodiesel and renewable diesel use, which is up 61 percent from 2018 and now accounts for 27 percent of total on-road diesel sold in California. California is also a world leader in the adoption of advanced alternative vehicles such as plug-in electric and hybrid vehicles. The state is the nation's largest market for zero-emission vehicles (ZEVs) due to California's regulation and vast portfolio of complementary policies. The state continues to lead in this area as recently shown by Governor Newsom's 100 percent ZEV sales for passenger vehicles target by 2035 (Newsom, 2020).

Transportation emissions are related to the amount of fuel burned. Combustion of fossil fuels such as gasoline and diesel produce GHGs that are counted towards California's inventory. On the other hand, emissions from the combustion of biofuels such as ethanol and biodiesel, which are derived from carbon that was recently absorbed from the atmosphere as a part of the global carbon cycle, are not counted pursuant to international GHG inventory practices (IPCC, 2006). Thus, displacing fossil fuels with biofuels can reduce the climate change impacts of the transportation sector.

The trends in the use of fossil fuels (blue, teal, and grey) and biofuels (yellow) are shown in Figure 8. Gasoline use is declining slightly, and biofuel use is increasing — trends contributing to the reduction in GHG emissions from transportation. Declining gasoline consumption is related to higher ethanol use, as well as to improved fuel economy and increased use of alternative fuel vehicles such as electric or hydrogen fueled vehicles. Biofuel diesel alternatives (i.e., biodiesel and renewable diesel) have been in use since 2010, and volumes are increasing rapidly. Between 2012 and 2019, biofuel diesel alternatives increased from 1 percent to 27 percent of the total transportation diesel use.



Figure 8. Trends in transportation fuel combustion from 2000 – 2019



Source: CARB, 2021a

\*Other fossil fuels include: aviation gasoline, jet fuel, LPG, residual fuel oil, and natural gas.

\*\*Biofuels includes gallons of ethanol, biodiesel, and renewable diesel

### Residential and Commercial

California’s steady population growth from 1990 through 2019 has been accompanied by an increased demand for housing, among other things. More housing often means additional demand for residential energy and increased associated GHG emissions, yet emissions from the residential and commercial sector decreased over the same period. Residential and commercial building code standards are updated regularly to improve building efficiency (e.g., insulation thickness, window design, lighting systems, and heating/cooling equipment specification). These energy efficiency standards have saved Californians billions of dollars in reduced electricity bills (CEC, 2015), and have reduced the emissions of GHGs and criteria air pollutants. The per capita electricity consumption in California is near the lowest in the nation, primarily due to mild weather and energy efficiency programs (EIA, 2021). Still, emissions from residential and commercial buildings have continued to rise since 2014, due in part to increases in natural gas use.

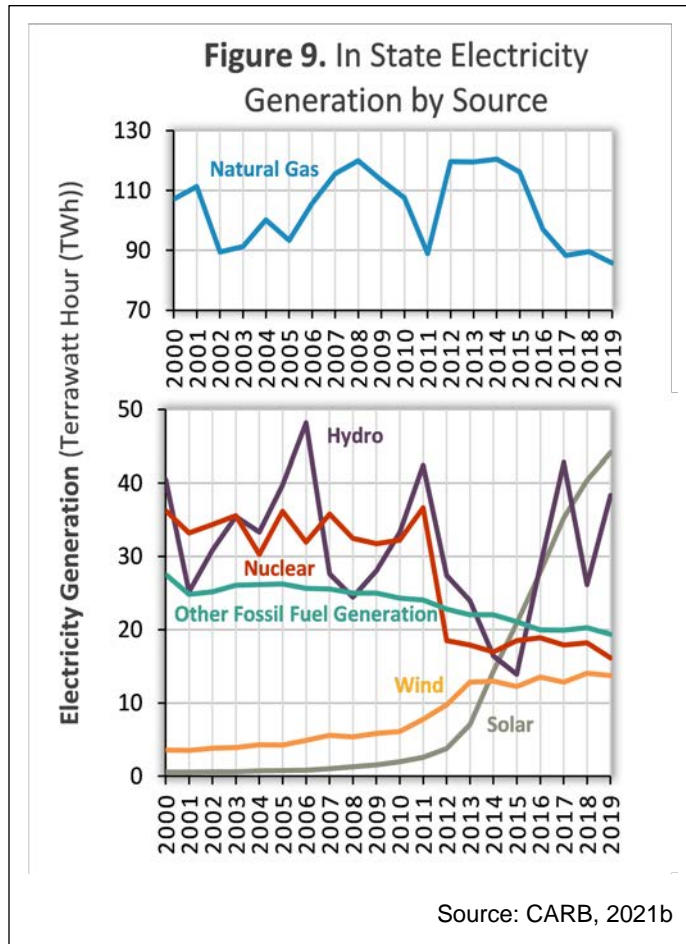
### Electric Power

The electric power sector includes two broad categories: in-state power generation (including the portion of industrial and commercial cogeneration emissions attributed to electricity generation) and imported electricity. Since the early 2000’s, the deployment of renewable and less carbon-intensive resources have facilitated the continuing decline in fossil fuel electricity generation. The Renewables Portfolio Standard (RPS) Program and the Cap-and-Trade Program continue to incentivize the dispatch of renewables



over fossil generation to serve California load. Higher energy efficiency standards also reduce growth in electricity consumption driven by a growing population and economy.

California’s in-state electricity is derived from a variety of sources (see Figure 9). Natural gas, which is used to produce the majority of in-state electricity, accounted for 39 percent of the electricity generation in 2019. Solar energy accounted for 20 percent, hydro accounted for 18 percent, and nuclear accounted for 7 percent of in-state generation. Nuclear power declined after the 2012 shutdown of the San Onofre Nuclear Generating Station. Hydro power reached historic lows in 2015 due to drought. An increase in solar and wind power has compensated for the decline in hydro power and nuclear generation in recent years. Wind, solar, hydro, and nuclear power are zero-emission sources. In 2019, California was the nation’s top producer of electricity from solar, geothermal, and biomass energy, and the state was second in the nation in conventional hydroelectric power generation (EIA, 2021).



Emissions from imported electricity peaked in 2004 and have since dropped 67 percent by 2019. Compared to 2011 levels, imports of hydro, solar, wind, and nuclear energy nearly tripled, while imports of coal energy dropped by 67 percent. In 2019, imports of hydro, solar, wind, and nuclear energy grew nine percent in one year.

Weather can also have notable influences on GHG emissions from the electricity sector. A warmer summer increases electricity demand for air conditioning, and consequently increases the emissions from power plants that must ramp up to meet the additional demand.

Short-Lived Climate Pollutants

Sources of methane and short-lived HFCs in California are shown in Figure 10. Livestock represents the largest source of methane. Methane is produced from livestock manure management and from the guts of ruminant animals such as cows. Organic waste deposited in landfills or managed in wastewater treatment plants also produce



methane emissions. As the primary component of natural gas, methane is also emitted by oil and gas extraction and during its storage, processing, and transport. Natural gas is used for many purposes including electricity production and heating.

Figure 10. 2019 Sources of short-lived climate pollutants\*



Source: CARB, 2021b

\*Based on the 2019 edition of the GHG inventory and 100-year GWP

Short-lived HFCs are used as replacements for ozone-depleting substances that are being phased out under the Montreal Protocol (UNEP, 2016). The majority of HFC emissions comes from refrigeration and air-conditioning systems used in the residential, commercial, industrial, and transportation sectors. Foams, aerosols, solvents, and fire protection are other sources of HFCs.

### Climate Change Policies and Regulations

California’s pioneering efforts in the adoption and implementation of policies are reducing GHG emissions. The California Global Warming Solutions Act of 2006 (Nuñez, Chapter 488, Statutes of 2006), also known as Assembly Bill (AB) 32, established the nation’s first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective GHG emissions reductions. AB 32 set a goal of reducing GHG emissions to the 1990 level by 2020 and requires the state to complete a Climate Change Scoping Plan that lays out the path to meet the emissions reduction target, and to update that plan at least every five years. The first Climate Change Scoping Plan was adopted by the Board in 2008 (CARB, 2008). Senate Bill 32 (Pavley, Chapter 249, Statutes of 2016) codified in statute the goal of further reducing GHG emissions to 40 percent below the 1990 level by 2030. In 2017, the Board adopted the 2017 Climate Change Scoping Plan, which lays out the path to meet this target (CARB, 2017). Executive Order B-55-18 calls for achieving carbon neutrality no later than 2045, and to achieve and maintain net negative emissions thereafter. As of mid-2022, CARB is working with state agencies on the next Scoping Plan update, which will identify a technologically feasible and cost-effective path to achieve carbon neutrality by no later



than 2045 while also assessing the progress the state is making towards reducing its greenhouse gas emissions by at least 40 percent from 1990 levels by 2030. A complete list of climate change legislation and executive orders can be found in the appendix.

### ***Technical considerations***

#### Data characteristics

A GHG inventory is an estimate of GHG emissions over a specified area and period from known sources or categories of sources. Emission inventories generally use a combination of two basic approaches to estimate emissions. The top-down approach utilizes nationwide or statewide data from various federal and state government agencies to estimate emissions. The bottom-up approach utilizes activity data (e.g., fuel quantity, animal population, tons of waste deposited in the landfill) to compute unit level emissions that are then aggregated to the state level for a particular source category. In either approach, calculation assumptions are made to estimate statewide GHG emissions from different levels of activity data. These calculations typically reference the 2006 IPCC Guidelines for National Greenhouse Gas Inventories or the U.S. Environmental Protection Agency's national GHG emission inventory, but also incorporate California-specific methods and considerations to the extent possible.

#### Strengths and limitations of the data

The methods used to develop the California GHG emission inventory are consistent with international and national inventory guidelines to the greatest extent possible. Emission calculation methodologies are evaluated over time and refined by incorporating the latest scientific research and monitoring activities.

The California GHG inventory includes emissions from anthropogenic sources located within California's boundaries. Pursuant to AB 32, California's inventory also includes imported electricity. The inventory, however, excludes emissions that occur outside California during the manufacture and transport of products and services consumed within the state across all sectors. On the other hand, California is a net exporter of multiple products, especially agricultural commodities. California exported about a quarter of all agricultural products (CDFA, 2014). The state's GHG inventory includes the carbon sequestered in California-produced agricultural products that are exported and consumed outside the state. In addition, GHG mitigation effects may cross geographic borders as part of international and sub-national collaboration, or as a natural result of implementation of state programs. The state's GHG emission inventory does not account for emission reductions outside of its geographic border that may have resulted from California's adopted programs.



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**APPENDIX.**

**California's Climate Change Legislation, Executive Orders, and Other References**

**AB 32** (Nuñez and Pavley, Chapter 488, Statutes of 2006),

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**AB 74** (Ting, Chapter 23, Statutes of 2019),

[https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill\\_id=201920200AB74](https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB74)

**AB 398** (Garcia, E., Chapter 135, Statutes of 2017),

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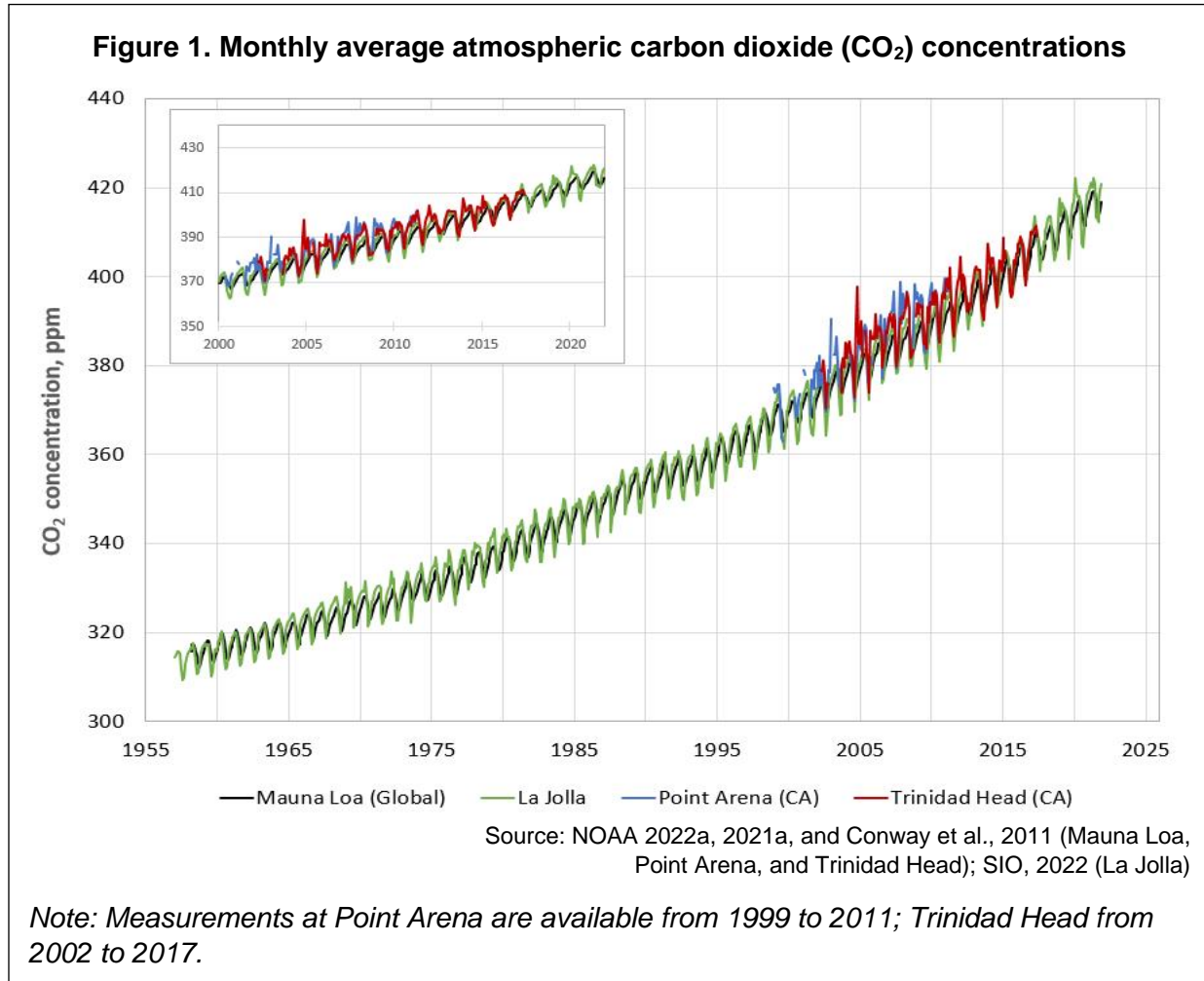
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## ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS

Atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and certain fluorinated gases continue to increase globally and in California. The annual average global concentration of carbon dioxide was 414 parts per million (ppm) in 2020, and 416 ppm in 2021\*, with a maximum monthly average of 419 parts per million in May of 2021.



### What does the indicator show?

Atmospheric concentrations of greenhouse gases (GHG) are increasing globally, as illustrated in Figures 1 to 4. These graphs show the ambient concentrations of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and a variety of fluorinated gases (F-gases) at the global background site of Mauna Loa on the island of Hawaii, as well as at regional background sites in California. The measurements are presented in parts per million (ppm) for CO<sub>2</sub> and CH<sub>4</sub>, parts per billion (ppb) for N<sub>2</sub>O, 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).

\* Based on data retrieved in June 2022; the last year of data are considered preliminary.



Figure 1 shows the CO<sub>2</sub> measurements at Mauna Loa, and three coastal sites in California (La Jolla, Point Arena and, Trinidad Head). Measurements at Mauna Loa first began in 1958. In over six decades, the annual average CO<sub>2</sub> concentrations have increased from 315 ppm in 1958 to 416 ppm in 2021. Annual CO<sub>2</sub> concentrations have increased by an average rate of 1.6 ppm per year over the past decades, accelerating in the last five years to about 2.4 ppm per year (NOAA, 2022a). At all these sites, CO<sub>2</sub> displays a seasonal trend with increasing CO<sub>2</sub> observed from autumn through late winter and decreasing CO<sub>2</sub> from spring through late summer. This is due to seasonal biosphere-atmosphere interactions – that is, plants take up CO<sub>2</sub> in spring and summer, then decay and release CO<sub>2</sub> in fall and winter) along with subtle seasonal changes in anthropogenic fossil fuel use. In the northern hemisphere, CO<sub>2</sub> concentrations tend to increase as one moves north from the equator, largely a result of global population centers (and hence, sources of CO<sub>2</sub>) being located at higher latitudes. Thus, CO<sub>2</sub> levels at the California sites tend to be slightly higher than those at Mauna Loa, and levels at the two Northern California sites (Trinidad Head and Point Arena) tend to be slightly higher than those at the Southern California site (La Jolla). For example, annual average CO<sub>2</sub> at La Jolla has been 1.2 ppm higher than Mauna Loa over the past ten years. The 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 CO<sub>2</sub>, respectively.

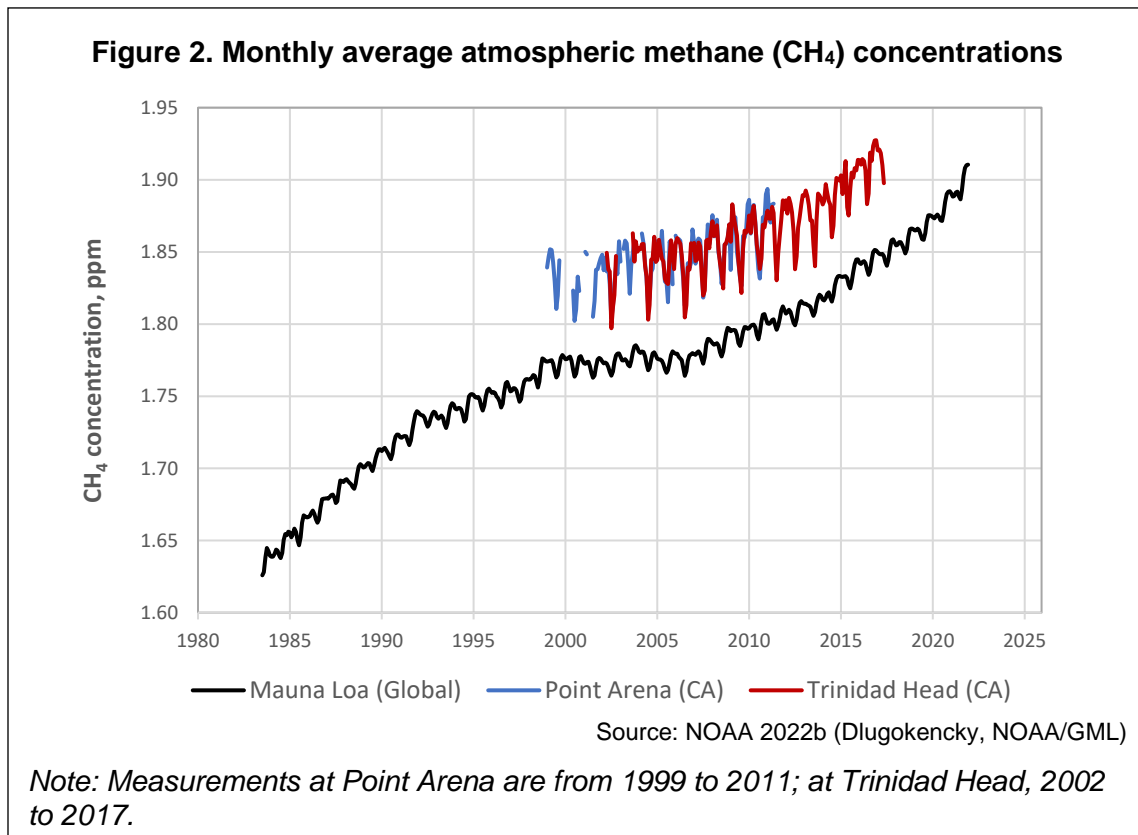


Figure 2 shows the atmospheric measurements of CH<sub>4</sub> at Mauna Loa since 1983, and at the California coastal sites, namely Point Arena and Trinidad Head, since 1999 and



2002, respectively. Global CH<sub>4</sub> 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. CH<sub>4</sub> concentrations in the pre-industrial era (i.e., pre-1750) were approximately 0.7 ppm (IPCC, 2013). By contrast, today’s atmospheric CH<sub>4</sub> concentrations exceed 1.9 ppm at Mauna Loa and the California sites – an increase of over 150 percent (NOAA, 2022b). Similar to, but to a greater extent than, CO<sub>2</sub>, the CH<sub>4</sub> concentrations at the California regional background sites are higher than those observed at Mauna Loa. This is due to a strong latitudinal gradient that promotes elevated CH<sub>4</sub> concentrations in the northern latitudes, where there are more human activities that lead to greater emissions (Frankenberg et al., 2005).

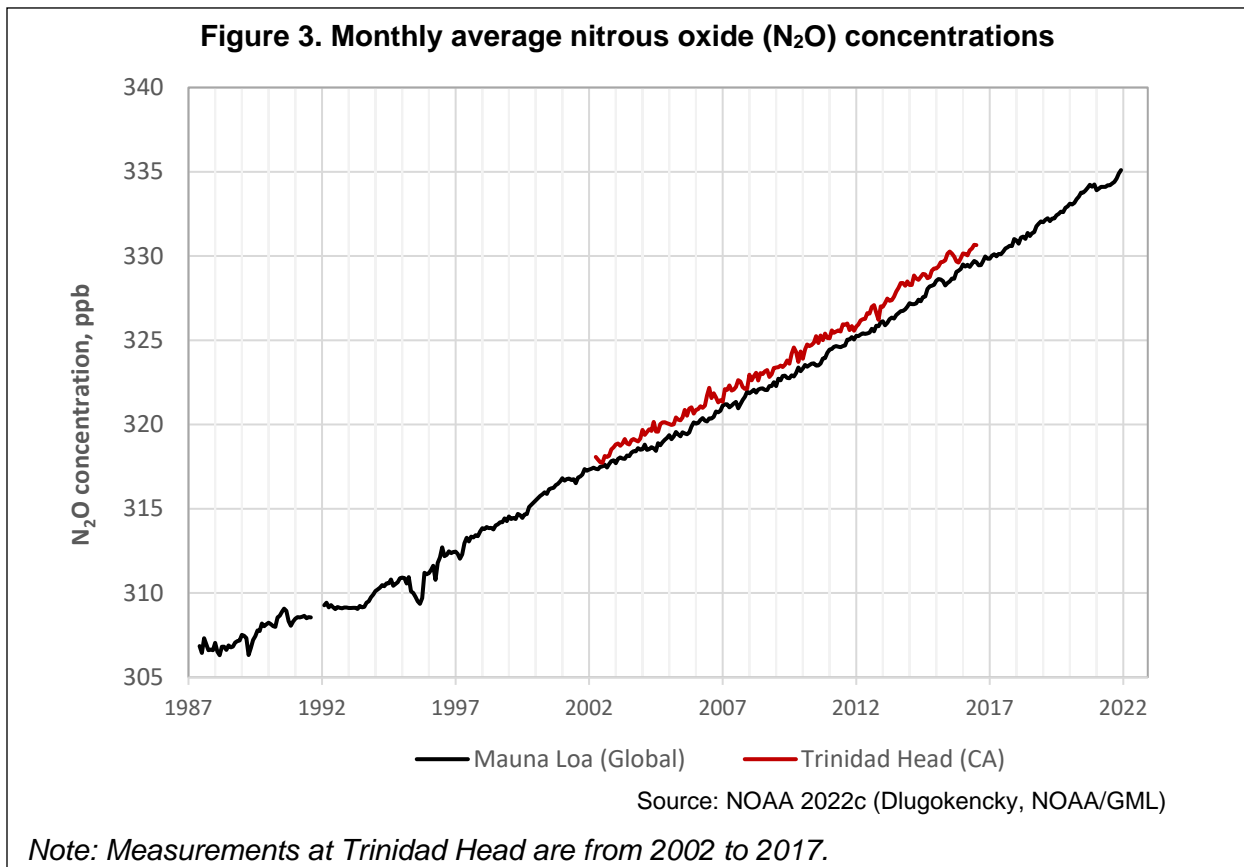


Figure 3 shows the atmospheric concentrations of N<sub>2</sub>O at Mauna Loa, which are available from 1987 to present, and Trinidad Head, which are available from 2002 to 2017. Global N<sub>2</sub>O concentrations have been increasing at a rate of approximately 0.7 ppb per year over the past few decades, and are now approximately 24 percent greater than the pre-industrial levels of 270 ppb (NOAA, 2022c). Unlike CO<sub>2</sub> and CH<sub>4</sub>, global N<sub>2</sub>O concentration trends do not display a strong seasonal cycle in the lower atmosphere.



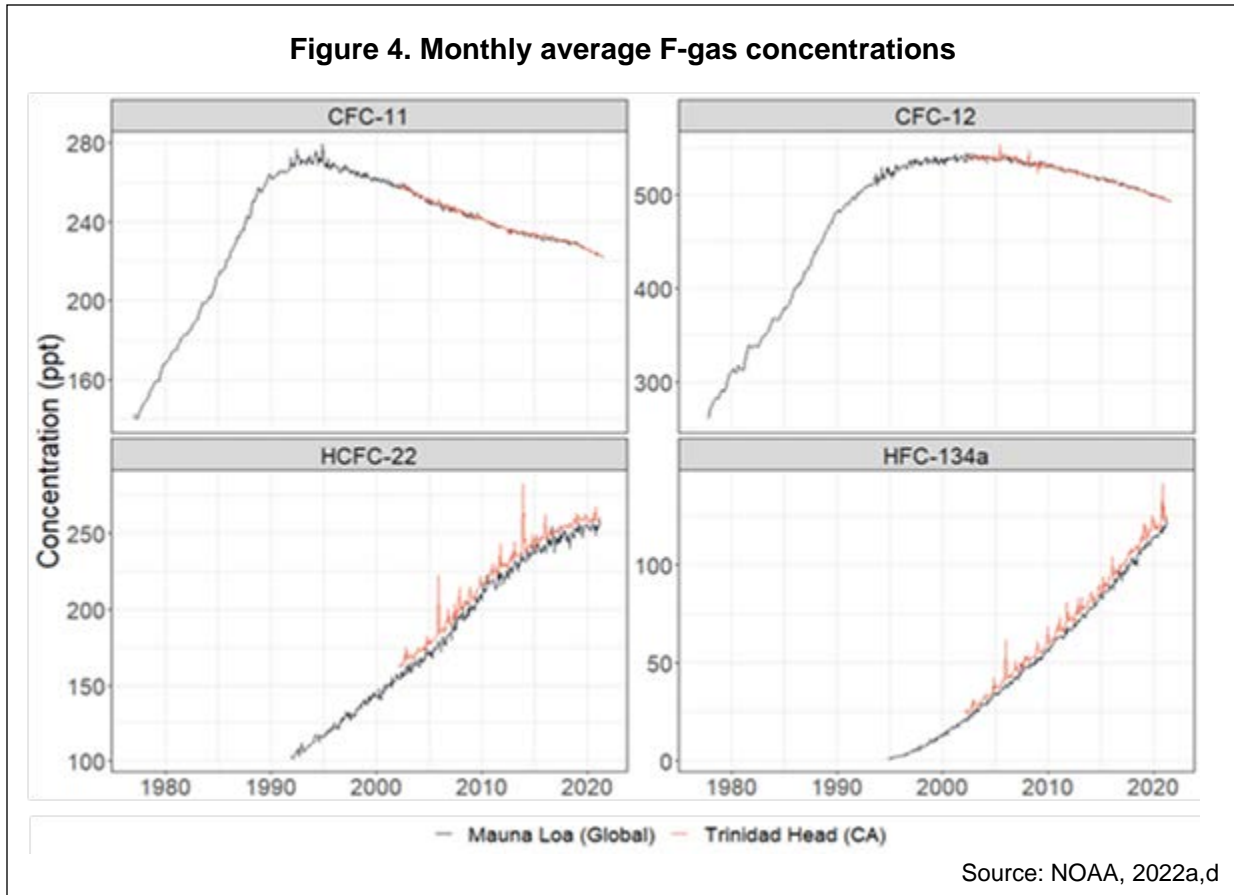


Figure 4 shows the atmospheric concentrations at Mauna Loa and Trinidad Head of select F-gases, which are a class of synthetic chemicals that includes chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). The figure shows the four most prevalent F-gases at Mauna Loa: trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), chlorodifluoromethane (HCFC-22), and 1,1,1,2-tetrafluoroethane (HFC-134a). F-gases began to appear in the atmosphere in the 20<sup>th</sup> century as a result of their usage as refrigerants and propellants; pre-industrial F-gas concentrations are assumed to be zero.

While F-gases are potent GHGs with global warming potentials that can be hundreds to thousands of times stronger than CO<sub>2</sub>, interest in atmospheric measurements of F-gases first began in the 1970's when they were linked to the destruction of stratospheric ozone (i.e., the "ozone hole") (Molina and Rowland, 1974). CFCs are strongly ozone-depleting, and their production and use were halted in 1996 under the Montreal Protocol (UNEP, 2012). Consequently, their global ambient concentrations have been slowly decreasing since the mid-1990s. Although no new emissions are expected, these gases have atmospheric lifetimes of decades, that is, they remain in the atmosphere for decades after they are released. With no new emissions, CFCs are well-mixed

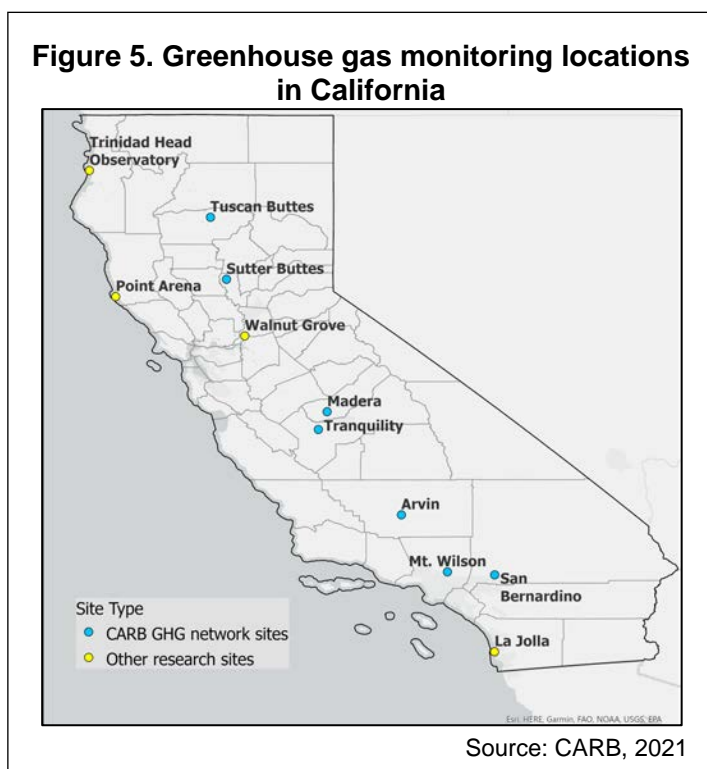


throughout the atmosphere and there is no latitudinal gradient in atmospheric CFC concentrations. Thus, Mauna Loa and Trinidad Head have nearly identical CFC levels.

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. Although 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, although the concentrations have begun to plateau in recent years as global phase-outs have ramped up. HFCs are modern refrigerants, such as HFC-134a, 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, HFC-134a concentrations have been increasing since it was first detected in the atmosphere in the 1990s. Unlike CFCs and HCFCs, HFC-134a concentrations have not begun to plateau or decrease, instead maintaining a growth rate of 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.

California has undertaken additional efforts to track the changes in ambient GHG concentrations at several monitoring sites located throughout the state. Figure 5 shows the seven GHG monitoring network sites operated by the California Air Resources Board (CARB), a research monitoring site operated by the Lawrence Berkeley National Laboratory at Walnut Grove, and the three coastal background sites operated by NOAA (NOAA, 2021a). These stations measure well-mixed regional air, providing monitoring data which can be used to understand how GHG concentrations are changing in California relative to the global trends. For example, the Walnut Grove station, an inland tower located near Sacramento, provides the signature of regional emissions from portions of Northern and Central California; the Mount Wilson site integrates remote sensing measurements (similar to the data products from satellites) at 33 locations across the

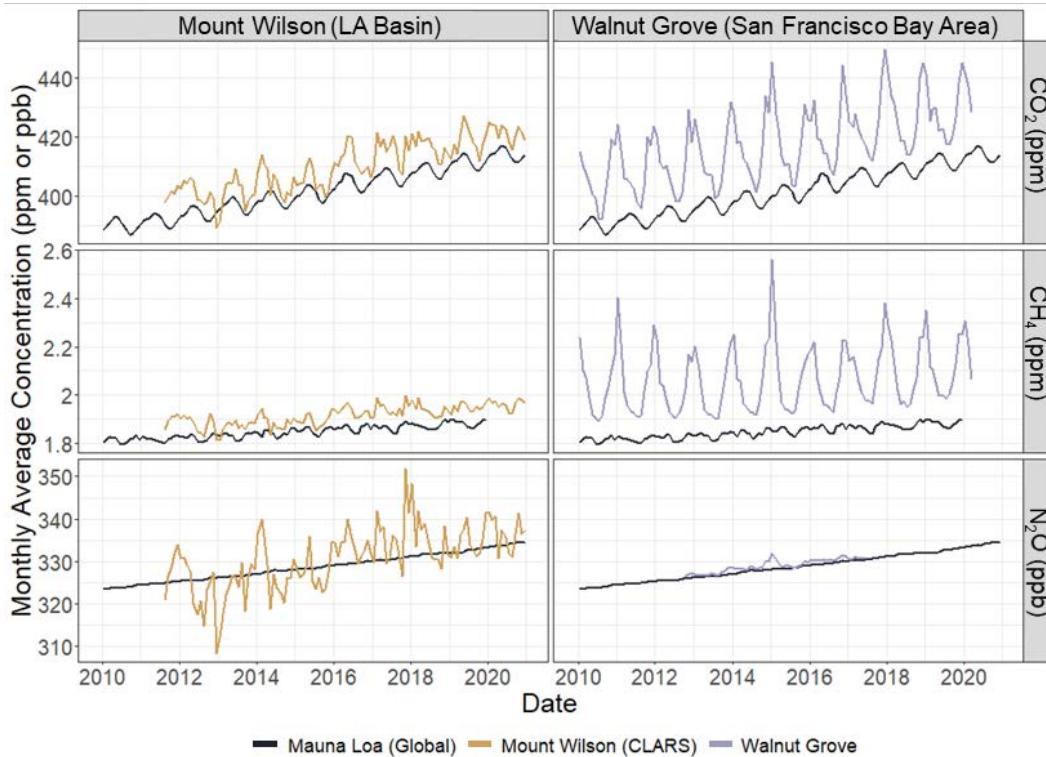
**Figure 5. Greenhouse gas monitoring locations in California**



Los Angeles (LA) air basin to yield basin-wide concentrations (see “Technical considerations” section).

Figure 6 shows monthly averaged CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O concentrations measured at Mount Wilson representing the LA basin, along with in-situ observations from the Walnut Grove site. As a global background reference, observations from NOAA’s Mauna Loa Observatory are also included in each graph.

**Figure 6. Comparison of monthly average atmospheric GHG concentrations at a global background site and two regional background sites**



Sources: Zhao and Sander, 2021 (Mount Wilson);  
Fischer and Jeong, 2016 (Walnut Grove);  
NOAA 2022a (Mauna Loa)

CO<sub>2</sub> observations from Mount Wilson track the global background well, albeit with larger variabilities and higher monthly average concentrations as a result of local emissions from the LA basin (Figure 6, top left panel). The average CO<sub>2</sub> concentration in the LA basin increased from roughly 400 ppm in 2011 to over 420 ppm by 2020. Similarly, the CO<sub>2</sub> concentrations at the Walnut Grove site were also higher than at Mauna Loa for a given year but had considerably larger inter- and intra-annual variability than the Mount Wilson observations. As noted above, the measurements at Mount Wilson represent a “basin average” number, while the Walnut Grove measurements reflect CO<sub>2</sub> at one location and are more sensitive to local emission sources. The more pronounced





seasonal pattern at the Walnut Grove site can also be attributed to its location as a receptor site for upwind sources from the Bay Area, as well as seasonal changes in mixed layer depths, which trap air pollution emissions closer to the ground during cooler months.

Observations from Mount Wilson and Walnut Grove also show higher CH<sub>4</sub> values and larger variabilities relative to the Mauna Loa background, which is due to the impact of local emissions in their respective regions (i.e., the LA basin and the San Francisco Bay Area). Similar to CO<sub>2</sub>, larger inter- and intra-annual variability in CH<sub>4</sub> is observed at Walnut Grove. This is likely due to fundamental differences between the CLARS remote sensing technique used at Mount Wilson and the in-situ measurement technique used at Walnut Grove, and the proximity of the latter site to local CH<sub>4</sub> emission sources.

Annual N<sub>2</sub>O concentration trends measured by the CLARS remote sensing instrument show a similar trend in the LA basin as those measured at Mauna Loa, but with larger interannual variability. By contrast, the trend in N<sub>2</sub>O concentrations at Walnut Grove closely mirrors the global trend, which are both increasing by approximately 1 ppb per year.

### ***Why is this indicator important?***

Global temperatures are directly linked to GHG levels in the atmosphere (IPCC, 2021). The 2015 Paris Agreement aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C above pre-industrial levels (UNFCCC, 2016). GHG emissions reduction targets have been established to prevent atmospheric concentrations from reaching levels at which catastrophic and irreversible impacts occur (see *Greenhouse gas emissions indicator*). Atmospheric GHG concentrations help track changes in the emissions of anthropogenic drivers of climate change and their accumulation in, and removal from the atmosphere.

CO<sub>2</sub> is a long-lived GHG responsible for roughly 65 percent of the total warming effect caused by GHGs globally. It contributes to over 84 percent of the current GHG emission inventory in California on a 100-year timescale (CARB, 2020a; WMO, 2016). Since CO<sub>2</sub> is typically well-mixed in the atmosphere, measurements at remote sites can provide integrated global background levels. The first and the longest continuous measurements of global atmospheric CO<sub>2</sub> levels were initiated by Charles D. Keeling in 1958 at Mauna Loa. For the first time, these measurements documented that atmospheric CO<sub>2</sub> levels were increasing globally. In the 1980s and the 1990s, it was recognized that greater coverage of CO<sub>2</sub> measurements was required to provide the basis for estimating the emission impacts of sources and sinks of atmospheric CO<sub>2</sub> over land as well as ocean regions. Since CO<sub>2</sub> remains in the atmosphere for many centuries, its atmospheric levels can continue to increase even if its emissions are significantly reduced.

Atmospheric CH<sub>4</sub>, N<sub>2</sub>O, and F-gases contribute roughly 17 percent, 6 percent, and 12 percent, respectively, of the warming (referred to as radiative forcing”) caused by globally well-mixed GHGs (IPCC, 2013; WMO, 2016). These pollutants could play an



even more important role owing to their greater 100-year global warming potentials (100-year GWP) as compared to that of CO<sub>2</sub> (GWP = 1). Despite a much shorter lifetime than that of CO<sub>2</sub>, these can cause significant climate impact in the near term, and are called short-lived climate pollutants (SLCPs). For instance, CH<sub>4</sub> has a 100-year GWP of about 28, and remains in the atmosphere for about 12 years before removal, whereas F-gases such as HCFC-22 and HFC-134a have GWPs of over 1,000, and can remain in the atmosphere for one to two decades. On the other hand, N<sub>2</sub>O has a GWP of 273 and remains in the atmosphere for roughly 120 years, which can result in long-term climate impacts (IPCC, 2021).

High-precision measurements, such as those presented in this indicator report, are essential for understanding GHG emissions from various sources – including human activities, atmospheric processes, plants, soils, and oceans. Tracking the life cycles of these GHGs provides information necessary for formulating mitigation strategies. Data on atmospheric GHG levels, in particular, are needed to project future climate change associated with various emission scenarios, and to establish and revise emission reduction targets (IPCC, 2013).

In California, regional GHG emission sources may contribute to enhancements in the concentrations of GHGs above global background levels. 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 GHG monitoring sites to infer the most likely distribution and strength of regional CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emission sources in California (Fischer and Jeong, 2016; Zhao et al., 2009, Cui et al., 2019).

#### **What factors influence this indicator?**

The concentrations of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and F-gases in the atmosphere reflect the difference between their rates of emission and their rates of removal. The majority of the changes observed in the global and regional GHG trends are directly related to human activities such as fossil fuel combustion, biomass burning, industrial processes, agricultural practices, and deforestation (IPCC, 2013). Additional discussion of factors affecting the emission of these GHGs in California is presented in the *Greenhouse gas emissions* indicator.

CO<sub>2</sub> is continuously exchanged between the land, oceans, and the atmosphere through physical, chemical, and biological processes (IPCC, 2021). Prior to 1750, the global background CO<sub>2</sub> concentration was estimated to be less than 280 ppm (WMO, 2016). During this period, the amount of CO<sub>2</sub> 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 the CO<sub>2</sub> concentration today derives primarily 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 emitted CO<sub>2</sub> is removed through natural processes within a century, about 20 percent remains in the atmosphere for many millennia (Archer et al., 2009). Consequently, atmospheric CO<sub>2</sub> will continue to increase in the atmosphere even if annual CO<sub>2</sub> emissions are



substantially reduced from present levels. It should be noted that, while increasing levels of atmospheric CO<sub>2</sub> are affecting climate, changes in climate are likewise affecting the processes that lead to CO<sub>2</sub> uptake from, and release into, the atmosphere (IPCC, 2021). For example, warming temperatures increase plant photosynthesis and thus CO<sub>2</sub> removal from the atmosphere, and wildfires release carbon stored by plants back into the atmosphere.

Atmospheric CO<sub>2</sub> concentrations reflect regional, as well as seasonal and inter-annual influences. Due to its higher fossil fuel emissions, the Northern Hemisphere has higher CO<sub>2</sub> concentrations than the Southern Hemisphere. Seasonal variations are attributed to seasonal patterns of plant growth and decay. Inter-annual variations have been attributed to El Niño and La Niña climate conditions; generally, higher-than-average increases in CO<sub>2</sub> correspond to El Niño conditions, and lower-than-average increases correspond to La Niña conditions (IPCC, 2021).

Atmospheric CH<sub>4</sub> originates from both natural and anthropogenic sources. CH<sub>4</sub> is emitted naturally from wetlands, oceans, termites, and geological sources. Anthropogenic sources of methane include rice agriculture, livestock, landfills, waste treatment, biomass burning, and fossil fuel and natural gas exploitation (i.e., extraction, transmission, distribution, and use). The production of CH<sub>4</sub> by many of these sources is influenced by anaerobic fermentation processes and climate variables (notably temperature and moisture). Atmospheric removal of CH<sub>4</sub>, on the other hand, is driven by oxidation processes, a process likewise affected by climate variables.

Atmospheric N<sub>2</sub>O 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). Human activities such as agriculture, fossil fuel combustion, wastewater management, and industrial processes account for 40 percent of total N<sub>2</sub>O emissions globally (US EPA, 2021). In California, N<sub>2</sub>O is emitted in large part from agricultural activities such as soil and manure management. In 2018, these contributed to roughly 54 percent of total statewide N<sub>2</sub>O emissions (CARB, 2020a). Most of the remaining 46 percent were attributed to the transportation, industrial, commercial, and residential sectors. Commercial and residential application of synthetic fertilizers over soil and lawn, in particular, plays a significant role in the nitrogen cycle; the release of N<sub>2</sub>O from such fertilizers has been shown to vary based on their rate of application and watering events.

N<sub>2</sub>O from fossil fuel combustion can vary significantly based on the technology, maintenance, and operation of combustion equipment (Graham et al., 2009; Huai et al., 2004). N<sub>2</sub>O is prevalent in the tail-pipe exhaust of motor vehicles when their engines and catalytic converters are operating at sub-optimal conditions. N<sub>2</sub>O is also typically generated as a by-product of synthetic fertilizer and other synthetic nitrogen production processes. On the other hand, N<sub>2</sub>O is removed from the atmosphere through bacterial activities and through photochemical reactions (US EPA, 2021).

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, the transmission and distribution of electricity, and vehicle air conditioning systems. CFC-11, CFC-12, HCFC-22, and HFC-134a emissions derive largely from fugitive leaks, venting during the maintenance and servicing of equipment, leaks from improperly maintained or damaged equipment, and the improper disposal of equipment (Gallagher et al., 2014).

International, national, and state regulations affect the use, emission, and eventual atmospheric concentrations of these substances. As noted above, pursuant to the Montreal Protocol of 1987, CFCs were phased out and banned in the United States in 1996. Most of the HCFCs were phased out of new production and consumption as of January 1, 2020. Driven by the phase-out of these ozone-depleting substances and by increased demand for refrigeration and air conditioning, HFCs became the fastest growing sources of GHG emissions in California and globally. They are now subject to a production and consumption phasedown under the Kigali Amendment (to the Montreal Protocol) starting in 2019 in ratified developed countries. The first group of developing countries ratified in the amendment will begin the phasedown in 2029. The second group of developing countries will have until 2032 to begin a phasedown. It is important to note that the Kigali Amendment has yet to be ratified by the United States. However, on December 27, 2020, U.S. Congress enacted the American Innovation and Manufacturing (AIM) Act of 2020. The AIM Act directs the U.S. Environmental Protection Agency (US EPA) to address HFCs by providing new authorities in three main areas: to phase down the production and consumption of listed HFCs, manage these HFCs and their substitutes, and facilitate the transition to next-generation technologies.

California Senate Bill 1383 (Statutes of 2016) requires statewide reduction of HFC emissions to 40 percent below 2013 levels by 2030 (CARB, 2017). In March 2018, California adopted high global warming HFC prohibitions in certain stationary refrigeration and foam end uses that were originally subject to the US EPA Significant New Alternatives Policy program (SNAP) rules which were partially vacated by a court case in 2017. Later in 2018, Senate Bill 1013 adopted the federal SNAP program in its entirety, which included a provision for an incentive program to increase the adoption of low global warming refrigerant technologies. Several other states that are part of U.S. Climate Alliance followed California in adopting similar rules in their respective jurisdictions. Despite existing measures, additional HFC emissions reductions are needed to meet California's 2030 statutory targets. In December 2020, CARB approved additional HFC measures (previously identified in CARB's short lived climate strategy plan), including strict GWP limits on new refrigeration and air-conditioning equipment, company-wide reduction targets for retail food refrigeration facilities, and a first of its kind program requiring the use of reclaimed refrigerant known as the Refrigerant Recovery Reclaim and Reuse or the R4 Program. In addition to national and international measures, California is currently evaluating further HFC reduction measures that will be needed to meet the Senate Bill 1383 target and long-term carbon neutrality goals.



## **Technical considerations**

### Data characteristics

The CO<sub>2</sub> data presented above are a combination of data from the Scripps Institution of Oceanography (SIO), the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA-ESRL), Lawrence Berkeley National Laboratory (LBNL), and CARB. In particular, NOAA-ESRL leads the Carbon Cycle Cooperative Global Air Sampling Network, an international effort which utilizes regular discrete samples from baseline observatories, cooperative fixed sites, and commercial ships (NOAA, 2021a). Air samples are collected weekly in glass flasks and CO<sub>2</sub> is measured by a non-dispersive infrared absorption technique (Keeling et al., 2001). The measurements at Mauna Loa were initiated by Charles D. Keeling of SIO, and date back to March 1958 (Conway et al., 2007). Monitoring at Point Arena was conducted from 1999 through 2011, and at Trinidad Head from 2002 through 2017. At the SIO La Jolla Pier, roughly one sample is collected each month during the period of record.

The Mount Wilson data shown here are from the California Laboratory for Atmospheric Remote Sensing (CLARS) Fourier Transform Infrared Spectrometer (CLARS-FTS) which measures the signatures of GHGs and pollutants from spectra of sunlight scattered from the land surface. CLARS-FTS measures the total number of trace gas molecules in the total optical path. Built by NASA's Jet Propulsion Laboratory, CLARS measures GHG emissions from sources across the Los Angeles (LA) air basin through remote sensing measurements at 33 locations. The CLARS facility has been measuring CO<sub>2</sub> and CH<sub>4</sub> continuously since September 2011 and N<sub>2</sub>O since May 2013, thus providing the longest available remote sensing data record that covers the entire LA basin (Zhao and Sander, 2021). The CLARS instrument builds up maps of GHG distributions from remote sensing measurements at 33 locations in the LA basin, similar to the data products from satellites. CLARS data presented here are representative of average basin-wide concentrations. This is quite different from in-situ ("tower") stations which bring a local air sample into the instrument for analysis. CLARS-FTS is similar to certain satellite instruments that measure trace gases (Fu et al., 2014; Wong et al., 2015).

Data collection at Walnut Grove tower began in 2007 through collaboration between researchers at LBNL and NOAA, with support from NOAA, the U.S. Department of Energy (DOE), California Energy Commission (CEC), and CARB. The site was equipped with an automated flask sampling system and real-time analyzers. These provide measurements of a suite of GHGs as well as other compounds including the radiocarbon of CO<sub>2</sub>. The Walnut Grove site is the first tall tower site in the world with continuous CH<sub>4</sub> measurements (under NOAA-ESRL's Global Monitoring Division).

Ambient CH<sub>4</sub> concentration data presented in this report were obtained from the NOAA-ESRL, LBNL, and CARB networks. NOAA-ESRL collected ambient air samples in evacuated flasks to detect CH<sub>4</sub> using a flame ionization detector (FID) integrated with a gas chromatograph (GC) system. LBNL and CARB network sites collect continuous air measurements of CH<sub>4</sub> using high-precision cavity ring-down spectroscopy (CRDS) with the same collection frequency and quality control protocols. CH<sub>4</sub> monitoring at Mauna



Loa began in 1983, Point Arena in 1999, and Trinidad Head in 2002; monitoring was discontinued at the California sites on 2011 and 2017, respectively.

Ambient N<sub>2</sub>O concentration data presented in this report were obtained from the NOAA-ESRL, LBNL, and CARB networks. NOAA-ESRL collected ambient air samples in evacuated flasks and utilized *in situ* systems to measure N<sub>2</sub>O. LBNL and CARB network sites use off-axis integrated cavity output spectroscopy to continuously measure N<sub>2</sub>O concentrations. Quality control protocols similar to those applied for CH<sub>4</sub> and CO<sub>2</sub> measurements are instituted to obtain high-precision N<sub>2</sub>O measurements.

Ambient F-gas concentration data presented in this report were obtained from the NOAA-ESRL network. NOAA-ESRL utilizes evacuated flasks to collect ambient air at Mauna Loa and analyzes samples using GC systems integrated with an electron-capture detector (ECD) and a mass spectrometer (MS). Data collection began in 2002 in Trinidad Head.

#### Strengths and limitations of the data

Measurement data from NOAA-ESRL undergo critical evaluation for quality control (NOAA, 2021b). 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 GHG trends over the past half century (SIO, 2012). 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 GHG 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.

CARB's Ambient GHG Monitoring Network and the Walnut Grove tower provide very useful data to study regional GHG emissions trends throughout California and to evaluate regional and statewide inventories in support of California's climate program (CARB, 2021b). These efforts rely heavily on highly accurate and precise measurements of ambient GHGs analyzed using state-of-the-science instruments. This inland network is comprised of eight monitoring stations located throughout California, and CARB and LBNL have equipped these stations with highly accurate and precise analyzers used to measure crucial climate influencers such as CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and black carbon (BC). Data from this network are used in several research studies. They also form the basis of a series of comprehensive statewide inverse receptor-oriented modeling efforts (Fischer and Jeong, 2016, Cui et al, 2019), as well as various trend analysis studies used to verify and inform the statewide GHG emission inventory in California.

Similarly, the CLARS instrument measures and tracks the GHG emissions from sources across the LA air basin. Unlike individual *in situ* monitoring stations, the CLARS



instrument has the unique capability to scan a large region multiple times a day through remote sensing. CLARS measurements are less sensitive to the height of the mixed layer and local sources, and unlike the in-situ monitors, CLARS data for some species must also be corrected for light scattering by aerosols.

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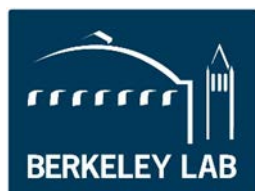
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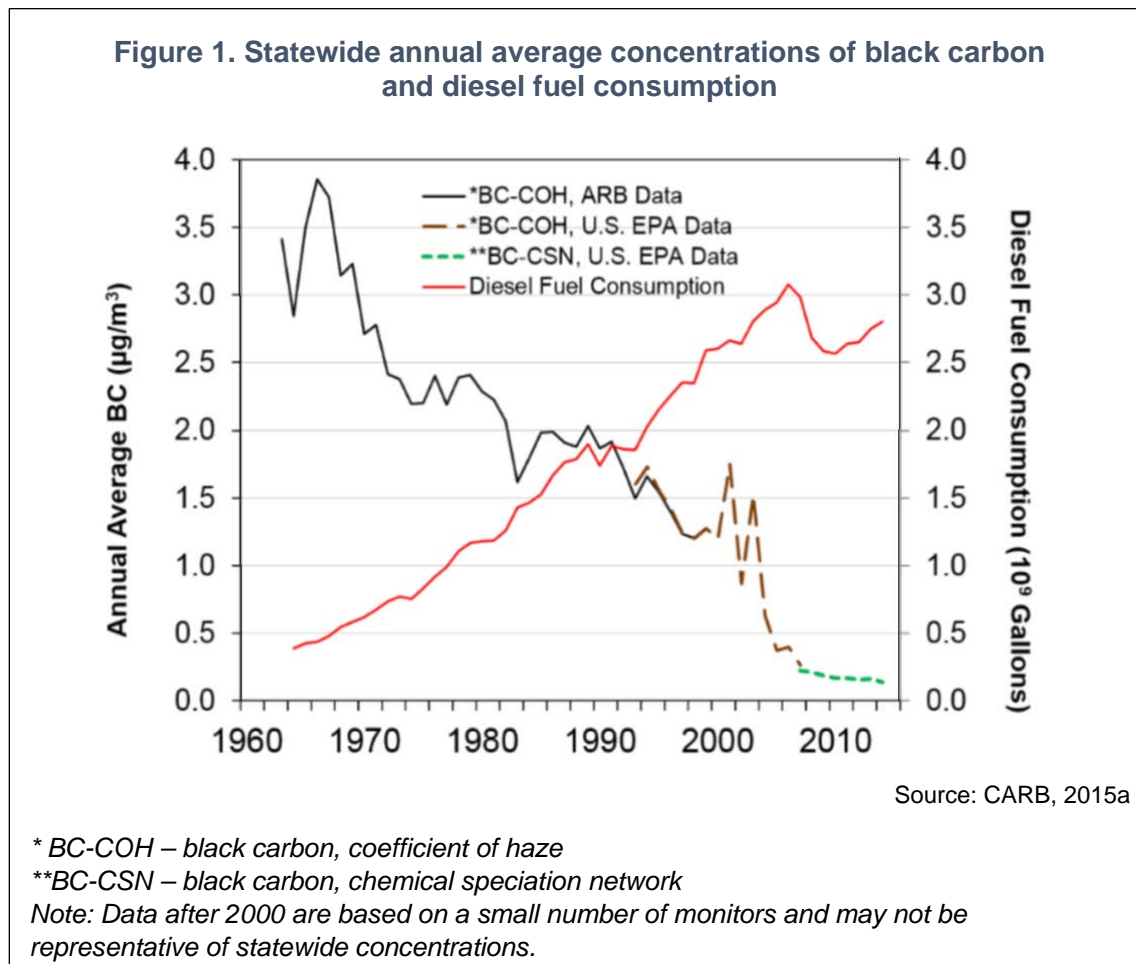
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## ATMOSPHERIC BLACK CARBON CONCENTRATIONS (NO UPDATE)

Atmospheric levels of black carbon, a major short-lived climate pollutant, have decreased dramatically in California since the 1960s.



### What does the indicator show?

Long-term data show that ambient black carbon (BC) concentrations in California have declined steadily (Figure 1). Annual average BC concentrations have dropped by more than 90 percent over the past 50 years, from an average of 3.4 micrograms per cubic meter ( $\mu\text{g}/\text{m}^3$ ) in the 1960s to  $0.14 \mu\text{g}/\text{m}^3$  since 2010. This dramatic decline in BC concentrations in the last five decades occurred despite a seven-fold increase in statewide diesel fuel consumption — the largest anthropogenic source of BC emissions in California. New emission standards and restrictions on diesel engines and biomass burning have significantly reduced atmospheric BC concentrations across the state (Kirchstetter et al., 2017).

Archived records of coefficient of haze (COH) were used to reconstruct historical BC concentrations. COH was one of the first measures of particulate matter (PM) pollution used by regulatory agencies and was determined to be a strong proxy for BC. (Please see *Technical Considerations* for a discussion of the data presented).



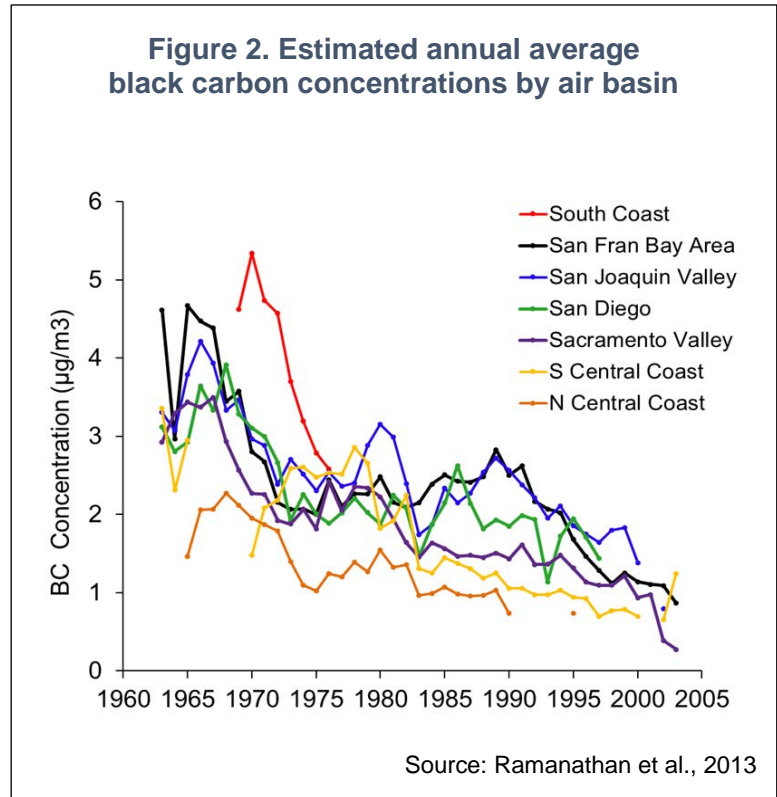
Although there is considerable variation, BC concentrations by air basin generally followed the decreasing statewide average trend. As shown in Figure 2, downward trends occur across all of the State’s major air basins from the mid-1960s to the early 2000s. BC concentrations were considerably higher in the South Coast Air Basin than in the rest of California, at least until the mid-1970s; the lowest BC concentrations were in the North Central Coast Air Basin.

**Why is this indicator important?**

Black carbon is a light-absorbing particle in the air, commonly known as soot. Scientists recently determined that BC may be the

second most important contributor to global warming after carbon dioxide (CO<sub>2</sub>) (Bond et al., 2013). However, it behaves very differently than long-lived greenhouse gases such as CO<sub>2</sub> do. While greenhouse gases trap heat from the Earth’s surface, BC contributes to climate warming by absorbing sunlight directly and releasing heat energy in the atmosphere. CO<sub>2</sub> remains in the atmosphere for hundreds of years, while BC particles are removed from the atmosphere by rain and by deposition after a few days or weeks. However, although BC has a shorter lifespan, it is a much more powerful warming agent than CO<sub>2</sub>. For example, one ton of BC has a warming effect equal to 900 tons of CO<sub>2</sub> over a 100-year period. Over 20 years, one ton of BC has the warming impact of 3,200 tons of CO<sub>2</sub> (Bond et al., 2013). Hence, it is considered a critical short-lived climate pollutant.

Black carbon influences the climate in several complex ways. In addition to its direct warming effects, BC particles can deposit on snow, glaciers, and sea ice. This darkens these light, frozen surfaces and reduces their reflectivity. Darker surfaces absorb more solar energy, causing snow and ice to melt more quickly (Hadley et al., 2010; Hadley and Kirchstetter, 2012). This early melting could significantly affect California’s summer water supplies, which rely heavily on snowmelt runoff from the Sierra Nevada. Less snowmelt runoff during the spring months, combined with warmer temperatures over already dry areas, increases wildfire risks — which can in turn release more BC particles.

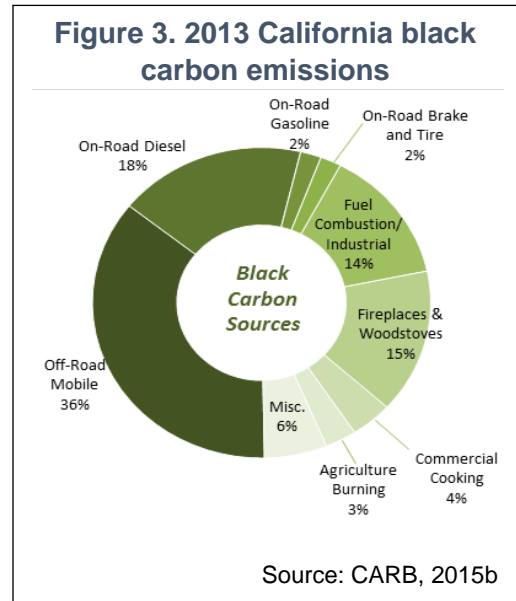


Black carbon can also change the reflectivity, stability, and duration of clouds. Its effects are different depending on how much of it is in the air and where it occurs in the atmosphere. Black carbon particles in a cloud layer can absorb solar radiation, heating the air in it, and leading to cloud evaporation and reduction. However, quantification of this indirect impact on the climate system is imprecise (Koch and Del Genio, 2010).

Reducing emissions of BC presents an opportunity to slow the rate of global warming in the near term. Black carbon is also a component of PM<sub>2.5</sub> air pollution (fine particulate matter that is 2.5 microns or less in diameter). PM<sub>2.5</sub> has been linked to respiratory and cardiovascular disease (US EPA, 2009). Hence, reduced BC emissions also provide public health benefits. Control measures are projected to lead to substantial reductions in BC emissions from mobile sources, preventing an estimated 5,000 premature deaths in the State each year (CARB, 2016). These reductions are especially beneficial to disadvantaged communities. For example, diesel particulate matter concentrations are highest along freight corridors and near ports and rail yards where disadvantaged communities are often located. Regardless of net climate forcing or other climatic effects, all BC mitigation options bring health benefits through reduced particulate matter exposure. A worldwide program along the lines of what is being done in California would avoid hundreds of thousands of premature deaths annually (Anenberg et al., 2011).

**What factors influence this indicator?**

In California, the major anthropogenic sources of BC in 2013 include a diesel-fueled mobile sources, fuel combustion and industrial processes, and residential fireplaces and woodstoves. Off-road mobile emissions account for over a third of statewide BC emissions. On-road mobile sources account for nearly a quarter of emissions, primarily from on-road diesel combustion, which contributes approximately 18 percent to California's BC emissions. On-road gasoline, as well as brake wear and tire wear emissions of BC are relatively small. Residential fireplaces and woodstoves currently account for approximately 15 percent of BC emissions, with another 14 percent attributable to fuel combustion and industrial processes.



Other anthropogenic sources include dust, waste disposal, residential natural gas combustion, and unplanned structure and car fires. These sources and the ambient concentrations of BC vary geographically and temporally. Emissions standards and



restrictions implemented on diesel engines and biomass burning activities have had a significant effect on decreasing ambient air BC concentrations across the State. In 2013, total anthropogenic BC emissions were about 38 million metric tons of carbon dioxide equivalent (MMT $\text{CO}_2\text{e}$ ), using the 20-year Global Warming Potential (GWP) value of 3,200 from the IPCC Fifth Assessment Report (IPCC, 2013).

Anthropogenic BC emissions do not include forest-related sources (i.e., wildfires and prescribed burning). Wildfire is the largest source of BC emissions in California, contributing an estimated 87 MMT $\text{CO}_2\text{e}$  annually (calculated as a ten-year annual average); prescribed fires, an important tool for forest managers, emit an estimated 4 MMT $\text{CO}_2\text{e}$ . (To provide a more representative view of emissions without large year-to-year variability driven by natural forces, forestry emissions are calculated as a ten-year average) (CARB, 2017).

As shown in Figure 1, the largest decline in BC concentrations occurred in the years before 1975, coinciding with the adoption of state and federal air quality regulations. These include tailpipe emission limits established by California in the mid-1960s, federal emission standards for stationary sources and motor vehicles adopted in the mid-1960s, and diesel emission controls introduced nationally in 1970. Between 1975 and 1990, BC levels declined more gradually, likely due to the replacement of older, more polluting diesel vehicles as a result of on-road heavy-duty diesel particulate matter emission standards adopted in 1973 by California. BC concentrations decreased more rapidly after 1990, despite intermittent increases in the early 2000s (Kirchstetter et al., 2008). Retrofitting of urban transit buses with oxidation catalysts, limits on sulfur content in diesel fuel, changes in diesel engine technology, and restrictions on agricultural burning and residential wood combustion, among other measures, contributed to the reductions.

Existing regulatory programs, including ongoing efforts to reduce tailpipe emissions from trucks and buses, will continue to reduce BC emissions. For example, further reductions are expected from stricter diesel engine emission standards implemented by the state in 2007 and the complementary low-sulfur fuel introduced nationally in 2006. To comply with federal air quality standards, control measures that reduce PM $_{2.5}$  pollution (including BC and other constituents) are projected to decrease BC emissions from mobile sources in California by 75 percent between 2000 and 2020 (CARB, 2016). Senate Bill 1383 (Chapter 395, Statutes of 2016) sets a target to reduce BC emissions by 50 percent below 2013 levels by 2030, with a focus on disadvantaged communities.

### ***Technical Considerations***

#### **Data Characteristics**

Because of their short residence time in the atmosphere and their strong dependence on local sources, particles exhibit high spatial and temporal variation, requiring frequent measurements at numerous sites to reliably track trends. However, few extensive records of particle concentrations are available. One of the first measures of PM pollution used by regulatory agencies, the coefficient of haze (COH), was determined to



be a strong proxy for BC, based on co-located field measurements of BC and COH. Archived records of COH, a now-retired measure of light-absorbing PM, were used to reconstruct historical BC concentrations. BC concentrations were inferred from COH data based on a relationship determined from statistical analyses (see Chapter 2.0 of Ramanathan et al., 2013). Statewide average BC concentrations were computed separately using data from CARB (1963 to 2000), and US EPA (1993 to 2007).

Where the US EPA and CARB datasets overlap, agreement is very good. The location and number of COH monitors operating in California has varied over time. From the mid-1970s to 2000, 30 or more COH monitors were in operation for the majority of the year, but these dropped to 15 by mid-2000 (mainly in the US EPA dataset). Hence, the data after 2000 are based on a smaller number of monitors, and may not be as representative of statewide concentrations.

Data from 2007 to 2017 are from the US EPA's Chemical Speciation Network (CSN). Since early 2000, about 17 CSN sites have been providing information on PM<sub>2.5</sub> concentrations in California's ambient air. Samplers operate on a 24-hour schedule from midnight to midnight, generally sampling every third day or every sixth day. CSN must meet all federal and state requirements for monitoring methodology and quality assurance. CSN is designed to track the progress of PM<sub>2.5</sub> emission reduction strategies through the characterization of trends of individual PM<sub>2.5</sub> species, including BC. Although the CSN network has been collecting BC data since 2000, the collection and analysis methods were different during the first few years of the program (Chow et al., 2007). The differences were significant enough to affect the trends, therefore data from the CSN network prior to 2007 are not presented in Figure 1.

#### Strengths and Limitations of the Data

For the purposes of climate change study, BC is defined as the carbon component of PM that absorbs light. A significant advantage of monitoring BC by an optical method is that it delivers results in real time with a high time resolution (in minutes). However, BC as a component of PM is difficult to measure. Methods that measure light absorption in PM assume that BC is the only light-absorbing component present. However, some components of organic carbon can also be light-absorbing. The impact of BC on climate forcing is well established, but the magnitude and wavelength dependence of absorption by organic carbon (often called brown carbon, a by-product of the biomass burning) is poorly constrained. Existing methods, such as using an enhanced thermal/optical carbon analyzer with multi-wavelength capabilities, can add value to current PM monitoring programs by providing a complete identification and quantitation of the carbonaceous component of ambient aerosols in near-real time.

Emissions inventories for climate change studies have focused primarily on greenhouse gases. Most of the important sources of greenhouse gases are also important sources of health-related pollutants. Likewise, BC is emitted primarily from combustion sources which are also important sources of health-related pollutants. California's BC inventory



relies on PM inventories coupled with speciation profiles that define the fraction of PM that is BC. However, it is a challenge to estimate statewide BC emissions, and to define speciation profiles for all sources. Hence, improved emissions inventory methodologies and tools developed for health-related pollutants can also provide opportunities for improving climate change emission inventories (and vice versa).

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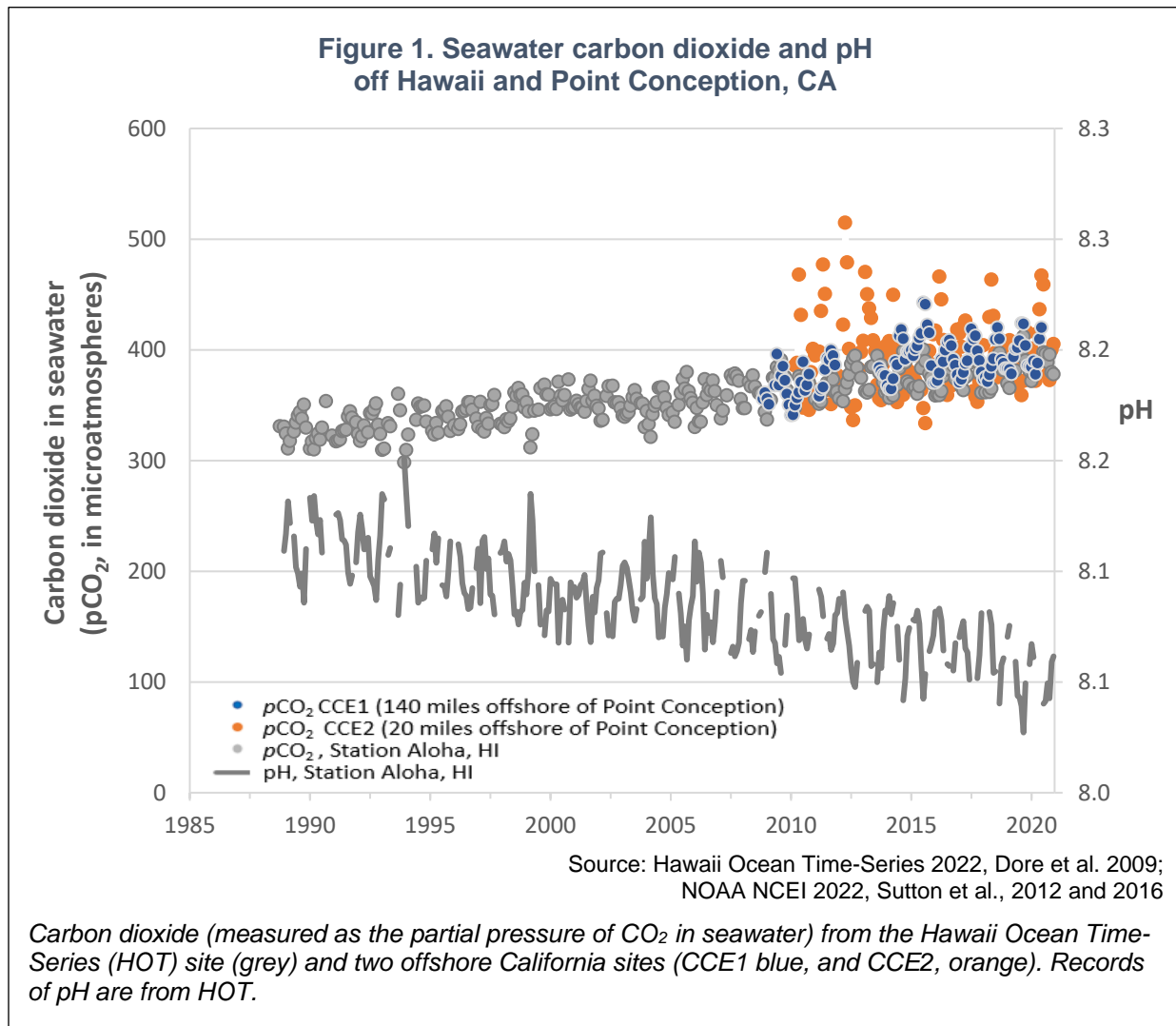
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### ACIDIFICATION OF COASTAL WATERS

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



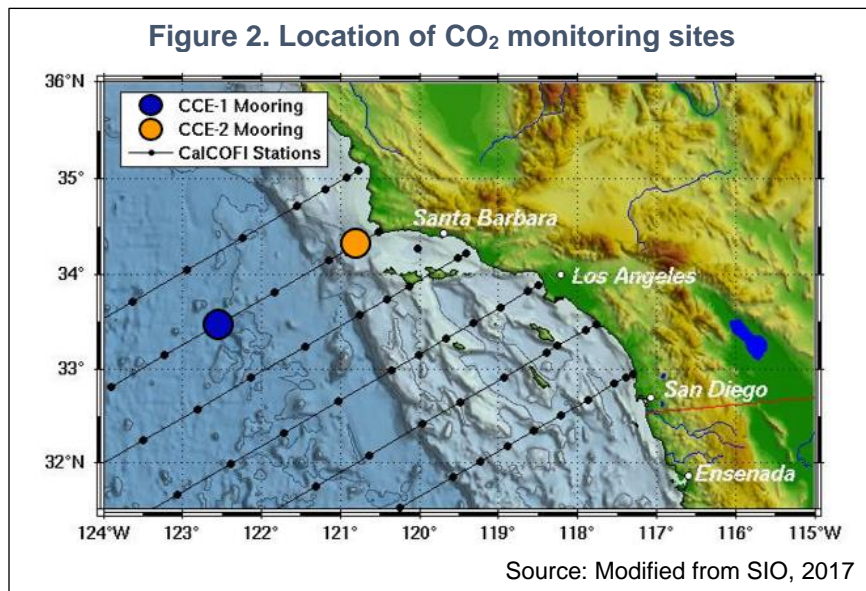
#### What does the indicator show?

This indicator shows that the oceans are becoming more acidic. This is clear in levels of carbon dioxide (CO<sub>2</sub>) and pH (a measure of acidity) in seawater off the coast of Hawaii, as shown in Figure 1. Levels of CO<sub>2</sub> are expressed as the partial pressure of carbon dioxide, or pCO<sub>2</sub> (which refers to the pressure that CO<sub>2</sub> contributes to the total pressure of the mixture of gases present in seawater). Off the coast of California, the levels of CO<sub>2</sub> measured since 2008 at “CCE1” located 140 miles off Point Conception near Santa Barbara are generally similar to those measured at similar time points at Station Aloha



off Hawaii, also shown in Figure 1. At CCE2, a second location 20 miles from Point Conception, levels show greater variability (values range from 330 to 520 microatmospheres ( $\mu\text{atm}$ )). This is likely due to its location closer to shore, where concentrations are influenced by seasonal changes in upwelling (Sutton et al., 2019; also see *Coastal ocean temperature* indicator). Upwelling is the wind-driven movement of deep, cool, carbon- and nutrient-rich ocean water to the surface, replacing the warmer, usually nutrient-depleted surface water.

Measurements at CCE1, which began in September 2010, provide the longest-running publicly available data on  $\text{CO}_2$  levels in seawater in California (there is a 21-month gap in measurements at CCE2). The record at both California locations are not long enough to discern trends. Figure 2 shows where sites CCE1 and CCE2 are located.



At Station Aloha,  $p\text{CO}_2$  levels have increased steadily at the rate of about  $1.8 \mu\text{atm}/\text{year}$ , and the pH has decreased at the rate of 0.002 unit per year over this time period. At seven long-term monitoring sites around the globe, measurements of  $p\text{CO}_2$  and pH show similar changes over the last three decades:  $p\text{CO}_2$  has increased by 1.29 to  $2.95 \mu\text{atm}/\text{year}$ , and pH has decreased by 0.0013 to 0.0025 unit/year (Bates et al., 2014). Monitoring at Station Aloha off Hawaii provides the longest-running measurements of ocean acidity in the North Pacific Ocean.

### ***Why is this indicator important?***

$\text{CO}_2$  is considered to be 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. Since the mid-1980s the ocean has absorbed approximately 20 to 30 percent of the  $\text{CO}_2$  released into the atmosphere by human activities (Bindoff et al., 2019; Canadell, et al., 2021; Friedlingstein et al., 2022); this process has significantly reduced the  $\text{CO}_2$  concentrations in the atmosphere and minimized some of the impacts of global warming (Rhein et al., 2013). As atmospheric  $\text{CO}_2$  concentrations continue to increase, so do  $\text{CO}_2$  concentrations in the ocean, changing the carbonate chemistry of seawater — a process termed “ocean acidification” (Caldeira and Wickett, 2003; Doney et al., 2009). The net result of adding  $\text{CO}_2$  to seawater is an increase in hydrogen ions ( $\text{H}^+$ ) — which increases seawater acidity and lowers seawater pH — along with a decrease in carbonate ion, a



fundamental ‘building block’ for organisms known as “calcifiers,” that forming shells or skeletons. The concentration of carbonate ions in seawater is commonly measured using the saturation state of aragonite, a soluble form of calcium carbonate used by calcifiers, expressed as the term  $\Omega$ . When  $\Omega$  is less than 1, exposed calcium carbonate structures begin to dissolve (Pershing et al., 2018). Global marine ecosystems face serious threats from ocean acidification, deoxygenation (see *Dissolved oxygen in coastal waters* indicator) and ocean warming (see *Coastal ocean temperature* indicator).

Tracking anthropogenic emissions of CO<sub>2</sub> and the distribution among the atmosphere, land, and ocean provides a better understanding of the global carbon cycle and informs the development of climate policies (Friedlingstein et al., 2022). Future scenarios project that the ocean and land will be less effective as sinks, and thus at slowing the accumulation of CO<sub>2</sub> in the atmosphere with increasing emissions (Gulev et al., 2021). Nevertheless, the ocean holds great potential for uptake and long-term storage of CO<sub>2</sub>. Approaches to enhance ocean’s carbon capacity without further acidifying ocean environments are an area of intense research. The National Academies has recommended a research agenda to assess the benefits, risks, and potential for responsible scale-up of ocean-based carbon dioxide removal strategies, and to ensure that no unintended and potentially irreversible harm to natural systems and coastal communities result (NASEM, 2021). Examples include nutrient fertilization to stimulate marine phytoplankton growth, artificial upwelling and downwelling, and seaweed cultivation.

Many economically and ecologically important West Coast species (such as oysters, mussels and crabs) have been documented to show direct responses to acidification (Chan et al., 2016). Although many studies have investigated the effects of ocean acidification on marine species, establishing threshold values for pH that sufficiently capture the concentrations at which harmful responses occur is challenging. For example, thresholds in for a species can vary with endpoints, life stage and spatial and temporal exposure patterns (Bednaršek et al., 2021a, b; Bednaršek et al., 2019). Further ocean acidification, combines with deoxygenation and ocean warming in producing these effects and how this occurs is not well understood. In a review of the literature on possible “tipping points” relating to ocean acidification, the authors concluded that the lack of long-term monitoring and the complexity of ecosystem responses to ocean acidification have made the detection of such tipping points difficult (Heinze et al., 2020).

Several biological processes in marine organisms are sensitive to changes in seawater chemistry. The best-documented and most widely observed biological effects on calcifiers (including plankton, mollusks, and corals) are decreased calcification rates and/or shell dissolution due to reduced carbonate ion levels under reduced pH conditions (e.g., Bednaršek et al., 2014; Bednaršek et al., 2021a, b; Bednaršek et al., 2019; Feely et al., 2018; Gaylord et al., 2011; Hodgson et al., 2018; Lord et al., 2019; Mekkes et al., 2021; Osborne et al., 2020; Rose et al., 2020; Swezey et al., 2020). Controlled laboratory experiments and field observations have documented decreased shell size/thickness in shellfish and elucidated these processes (Barton et al., 2012);



Gaylord et al., 2011; Hettinger et al., 2012 and 2013; Miller et al., 2009; Waldbusser et al., 2013). Impacts on calcifiers can be amplified across marine food webs when they affect sea snails (pteropods), single-celled amoeboid organisms (called foraminifera) and other key links in the marine food chain; can lead to the degradation of the habitat provided by corals, mussels, oysters and other structure-forming taxa; and can reduce the water filtration services provided by bivalves (e.g., Feely et al., 2016; Hollarsmith et al., 2020; Osborne et al., 2020; Mekkes et al., 2021). 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).

In lower pH ocean waters, organisms face greater challenges in maintaining internal acid-base balance, leading to effects on the physiology and behavior of marine species (e.g., Somero et al., 2016; Hodgson et al. 2018; Jellison et al., 2016; Gaylord et al., 2018; Contolini et al., 2020; Rose et al., 2020). Other potential effects of ocean acidification result from changes in the ionic form of marine nutrients and potentially harmful substances (such as metals); increased photosynthetic rates in carbon-fixing organisms; altered reproduction and survival in organisms; and reduced olfaction (sense of smell) in fish. Broader ecological consequences include trophic mismatch (Kroeker et al., 2021) and altered predator-prey and other species interactions, such as herbivory and competition (e.g., 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).

Regional biological indicators can help improve the understanding of impacts of ocean acidification and other stressors on California's varied smaller-scale ocean ecosystems (Duncan et al., 2019; Duncan et al., 2013). A comprehensive review and analysis of biological responses to ocean acidification has identified possible indicator species and variables to consider in selecting indicators of ocean acidification (Kroeker et al., 2013). Among the most important traits of candidate indicator species are sensitivity to the environmental factor of interest, ecological value, presence over a wide geographic extent, and accessibility and familiarity to local communities (Gaylord et al., 2018). Some potential indicators of the biological impacts of ocean acidification in California waters are:

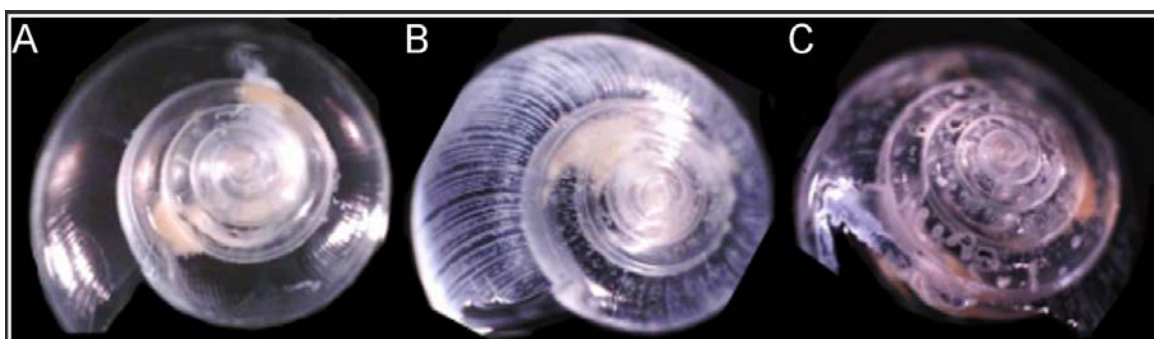
- The California mussel (*Mytilus californianus*), a familiar and well-recognized intertidal organism throughout the US West Coast. It is a classic “foundation species” that dramatically influences community structure both through its dominant status and its role in providing habitat (mussel beds) for hundreds of other species (Suchanek, 1992; Duncan et al., 2019; Rose et al., 2020). The distribution of *M. californianus* spans the entire west coast of the US (Morris et al., 1980; Rose et al., 2020), including most of the state's shoreline Marine Protected Areas. Life history can play a critical role in mussel response to ocean acidification: newly settled *M. californianus* retain larval shells which have been shown to be smaller when larval stages occurred in lower pH seawater; further, overall health is reduced when lower



pH conditions are combined with warmed waters (Gaylord et al., 2018; Rose et al., 2020). Not only are California mussels affected by changes in seawater chemistry, they are accessible on shore when tides recede. *M. californianus* has already been identified as an indicator species by two National Marine Sanctuaries in California (Gaylord et al., 2018).

- Krill, a fundamental and important component of the marine food web. Krill have been shown to be sensitive to ocean acidification, with responses that include reductions in growth rates and increased mortality (e.g., Cooper et al., 2017; McLaskey et al., 2016).
- Pelagic snails (pteropods), that have delicate shells subject to severe dissolution when exposed to low pH seawater (Duncan et al., 2019; Engström-Öst et al., 2019; Mekkes et al., 2021). Dissolution of shells of *Limacina helicina*, the most dominant pteropod within the California Current Large Marine Ecosystem, have been demonstrated to occur in waters with low levels of aragonite (the form of calcium carbonate used by marine calcifiers), thus underscoring the species' susceptibility to ocean acidification (Bednaršek et al., 2014; Bednaršek et al. 2018; Busch et al., 2014; Mekkes et al., 2021) (see Figure 3). Pteropods are ecologically important as prey for commercial fish species.

**Figure 3. Dissolution of pelagic snail shells exposed to corrosive seawater**



Source: Figure 7, Busch et al., 2014

Images of *Limacina helicina*, a pelagic snail, after week-long incubation in Puget Sound waters at the following levels of aragonite (a form of calcium carbonate,  $\Omega_a$ ) levels: [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.

The Fourth California Climate Assessment noted that “ocean acidification presents a significant and well-established threat to commercial fisheries and farmed shellfish, and therefore human coastal communities” (Sievanen et al., 2018). This supports a growing body of literature that explores the connections between ocean acidification, coastal economies, and human communities (e.g., Doney et al., 2020).



### **What factors influence the indicator?**

The Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report, concluded that the uptake of anthropogenic CO<sub>2</sub> 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 carbon dioxide is determined largely by the difference in the partial pressure of CO<sub>2</sub> between the atmosphere and the ocean; as the partial pressure of CO<sub>2</sub> 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 (including the Hawaii Ocean Time Series presented in Figure 1) collectively show consistent and coherent changes in the uptake of CO<sub>2</sub> by the ocean. At decadal time scales, the rate of ocean acidification in these open ocean surface waters generally approximates the rate of CO<sub>2</sub> increase in the atmosphere (Bates et al., 2014).

The air-sea CO<sub>2</sub> interchange – which is driven by differences in the amount of CO<sub>2</sub> in air compared to water -- is influenced by biologically-mediated reactions (photosynthesis, respiration, and precipitation and dissolution of calcium carbonate). Photosynthesis and respiration remove and add CO<sub>2</sub> to seawater, respectively. In coastal habitats, kelp forests and seagrass meadows can locally ameliorate high CO<sub>2</sub> concentrations by removal of CO<sub>2</sub> 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 locally reducing buffering capacity and increasing  $p\text{CO}_2$ .

While biological processes play an especially key role in determining shorter-term (daily to seasonal) variability in pH and  $p\text{CO}_2$  in seawater (Wootton et al., 2008; Hoffman et al., 2011), air-sea exchange processes dominate the longer-term interannual-to-decadal trends. Along the West Coast, ocean acidification adds to the already naturally high values of carbon dioxide in upwelled waters. The unique oceanography of the California Current Large Marine Ecosystem may provide early indication of the impacts of ocean acidification and decreasing dissolved oxygen; California's coastal waters are experiencing more acidified and lower oxygen conditions well earlier than most other regions (e.g., Feely et al., 2008; Hauri et al., 2009; Gaylord et al., 2018; Hodgson et al., 2018; Osborne et al., 2020). The interactions between upwelling, hypoxia, and ocean acidification are well explored (e.g., Cheresh and Fiechter, 2020).

In addition to seasonal patterns in ocean chemistry tied to upwelling processes, changes associated with large-scale climate oscillations such as El Niño and the Pacific Decadal Oscillation can alter the ability of oceanic waters to serve as either a sink or a source of CO<sub>2</sub>. This can occur through seawater temperature changes as well as through ecosystem variations that occur via complex physical-biological interactions (Chavez et al., 2007). For example, during El Niño, upwelling of high CO<sub>2</sub> waters is dramatically reduced along central California so that flux out of the ocean is reduced; at the same time, ocean uptake of CO<sub>2</sub> is also reduced because of lower photosynthetic activity, as nutrients that would have been carried to the surface by upwelled waters are less available. Modeled estimates of pH and *aragonite saturation state* (a measure of whether calcifying organisms will be able to form shells, or if shells are more likely to



dissolve) along the southern California coast from 1985 to 2014 suggest a persistent shift in ocean acidification-related seawater conditions from the decade prior to the strong 1997–1998 El Niño event to the decade after it (McClatchie et al., 2016). In the southern California Current System, subdecadal (2005–2011) estimates for pH and related parameters reveal a pronounced seasonal cycle and inter-annual variability in the upper water column (15–500 meters depth) (Alin et al., 2012). Changes in the local biogeochemistry, carbon chemistry, and saturation state were also documented during the 2014–2016 heat wave event on the California coast (Lilly et al., 2019).

The variability in the data of  $p\text{CO}_2$  levels in Figure 1 (CCE2 location) compared to open ocean waters (CCE1 location) reflects the more complex acid-base chemistry dynamic of coastal waters (NAS, 2010). In addition to upwelling and other climate-related processes, coastal waters can be affected by localized freshwater and atmospheric inputs, organic matter and nutrients from land, and processes in the underlying sediments. The seasonal, monthly, and daily variability that can occur from biological and oceanographic processes 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; IPACOA (shore stations), 2021; see references for URLs to access data from these stations). Knowledge of short-term variability of  $\text{CO}_2$  in seawater is important to interpret any 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 to 15 years at open ocean sites (such as CCE1, estimated at 12 years) and 16 to 41 years at coastal sites (such as CCE2, estimated at 24 years) (Sutton et al., 2019).

Despite the global nature and the widespread implications of ocean acidification, a unified policy response analogous to international efforts to limit greenhouse gas emissions has yet to be developed (Collins et al., 2019). Since it takes decades to millennia for the ocean subsurface to respond to changes at the surface, the ocean is already “committed” to changes resulting from current atmospheric greenhouse gas levels, 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 species on oceanographic cruises, calculation of aragonite saturation state, and shore-based observations of carbon chemistry in nearshore waters. These monitoring efforts are included in large-scale monitoring programs, for example within the US Integrated Ocean Observing System (IOOS) and the National Oceanic and Atmospheric Administration (NOAA) ocean acidification observing network, all carried out in collaboration with a wide range of national, regional, and international partners. Many of these efforts can be viewed in real time through an online data portal (IPACOA, 2021).





Integrated biological, chemical, and physical oceanographic monitoring may elucidate broad-scale impacts of 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; data are collected 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](#), and the [Consortium on the Ocean's Role in Climate](#).

Figure 1 features data from the Hawaii Ocean Time-series (HOT) program for comparison. This program has been making repeated observations of the chemistry, and biology of the water column at a station north of Oahu, Hawaii, since October 1988. Cruises are made approximately once per month to the deep-water Station Aloha located 62 miles north of Oahu, Hawaii. Calculated values of pH and  $p\text{CO}_2$  are obtained from measured parameters; direct measurements of pH are also made at sea.

Despite the central importance of data for detecting long-term changes in the ocean's carbon system, coordinated observing networks in the US coastal and estuarine waters did not exist until the early 2010s, following the establishment of NOAA's Ocean Acidification program (NOAA, 2021). 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 1980's) (Bates et al., 2014). 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).

#### Strengths and limitations of the data

Given that pH and/or  $p\text{CO}_2$  of seawater are variable in many of California's marine ecosystems, datasets of these carbonate chemistry parameters will need to be of sufficient length before trends beyond natural variability can be detected (Sutton et al., 2019). Hence, a limitation of the ability to detect long-term trends in carbonate chemistry off California's coast is that the monitoring sites have not been continuously operated, due to funding limitations, and many focused on ocean acidification were more recently initiated. Measurements of pH, in addition to  $p\text{CO}_2$ , will allow a more accurate and precise evaluation of 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). Ideally this will take shape via a robust, integrated monitoring system for ocean acidification and hypoxia that is integrated with biological monitoring.



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