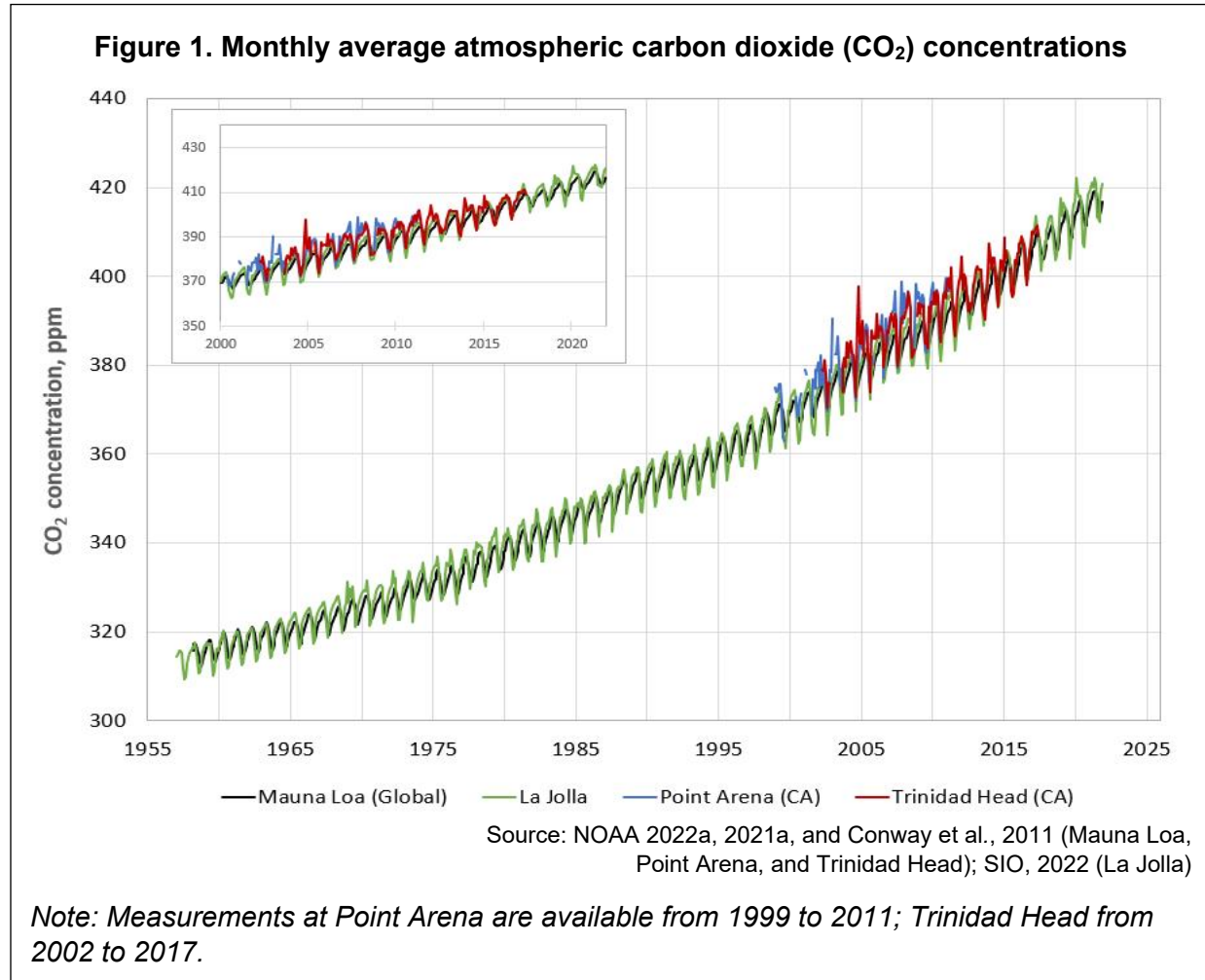## ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS

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.

Figure 1. Monthly average atmospheric carbon dioxide (CO$_2$) concentrations

Source: NOAA 2022a, 2021a, and Conway et al., 2011 (Mauna Loa, Point Arena, and Trinidad Head); SIO, 2022 (La Jolla)

Note: Measurements at Point Arena are available from 1999 to 2011; Trinidad Head from 2002 to 2017.

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$_2$), methane (CH$_4$), nitrous oxide (N$_2$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$_2$ and CH$_4$, parts per billion (ppb) for N$_2$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).

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

Figure 1 shows the CO_2 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_2 concentrations have increased from 315 ppm in 1958 to 416 ppm in 2021. Annual CO_2 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_2 displays a seasonal trend with increasing CO_2 observed from autumn through late winter and decreasing CO_2 from spring through late summer. This is due to seasonal biosphere-atmosphere interactions – that is, plants take up CO_2 in spring and summer, then decay and release CO_2 in fall and winter) along with subtle seasonal changes in anthropogenic fossil fuel use. In the northern hemisphere, CO_2 concentrations tend to increase as one moves north from the equator, largely a result of global population centers (and hence, sources of CO_2) being located at higher latitudes. Thus, CO_2 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_2 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_2, respectively.

Figure 2. Monthly average atmospheric methane (CH₄) concentrations

Source: NOAA 2022b (Dlugokencky, NOAA/GML)

Note: Measurements at Point Arena are from 1999 to 2011; at Trinidad Head, 2002 to 2017.
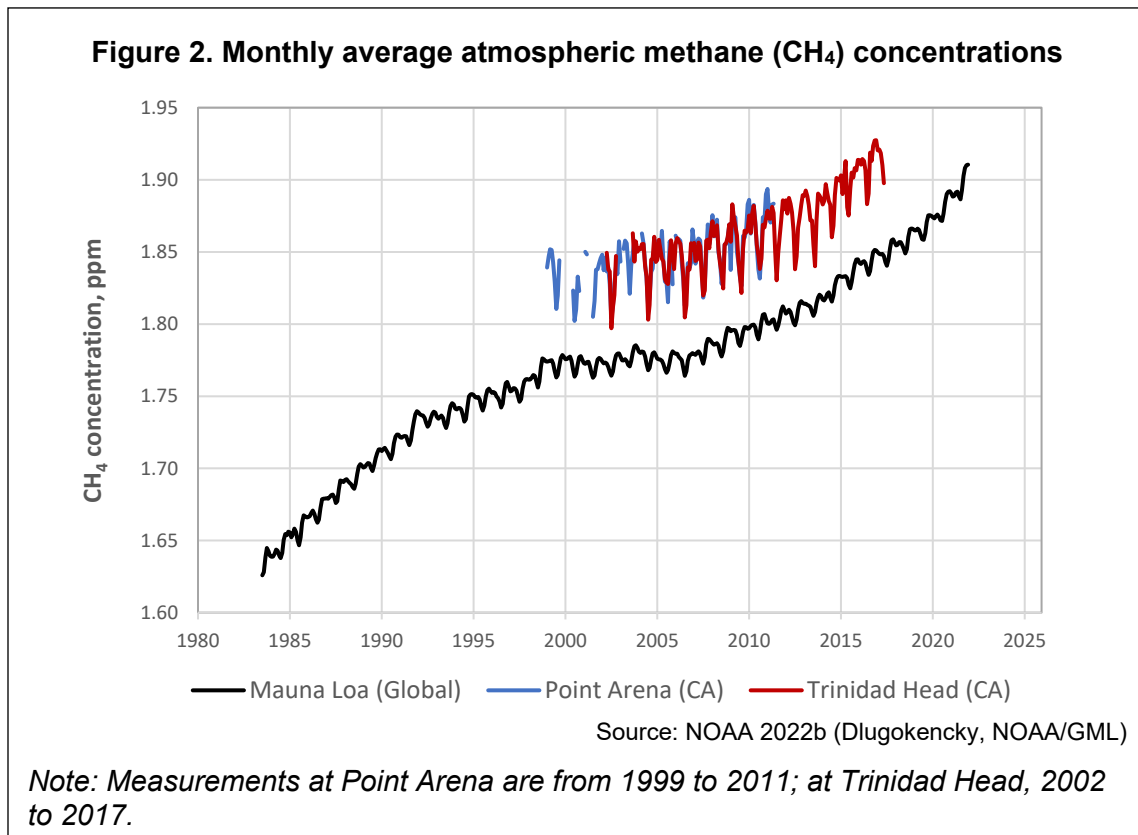
Figure 2 shows the atmospheric measurements of CH_4 at Mauna Loa since 1983, and at the California coastal sites, namely Point Arena and Trinidad Head, since 1999 and

2002, respectively. Global CH$_4$ 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$_4$ concentrations in the pre-industrial era (i.e., pre-1750) were approximately 0.7 ppm (IPCC, 2013). By contrast, today's atmospheric CH$_4$ 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$_2$, the CH$_4$ 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$_4$ concentrations in the northern latitudes, where there are more human activities that lead to greater emissions (Frankenberg et al., 2005).

Figure 3. Monthly average nitrous oxide (N$_2$O) concentrations

Source: NOAA 2022c (Dlugokencky, NOAA/GML)

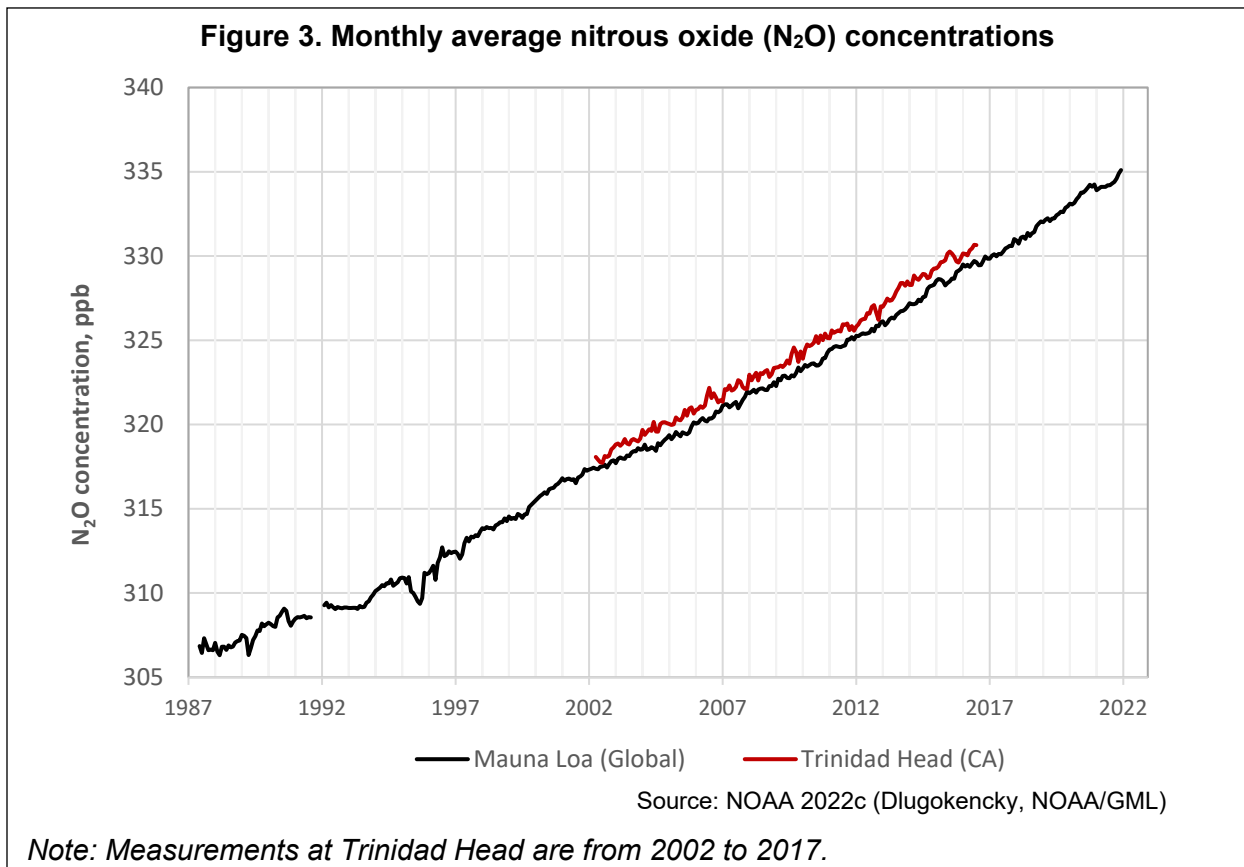*Note: Measurements at Trinidad Head are from 2002 to 2017.*

Figure 3 shows the atmospheric concentrations of N$_2$O at Mauna Loa, which are available from 1987 to present, and Trinidad Head, which are available from 2002 to 2017. Global N$_2$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$_2$ and CH$_4$, global N$_2$O concentration trends do not display a strong seasonal cycle in the lower atmosphere.

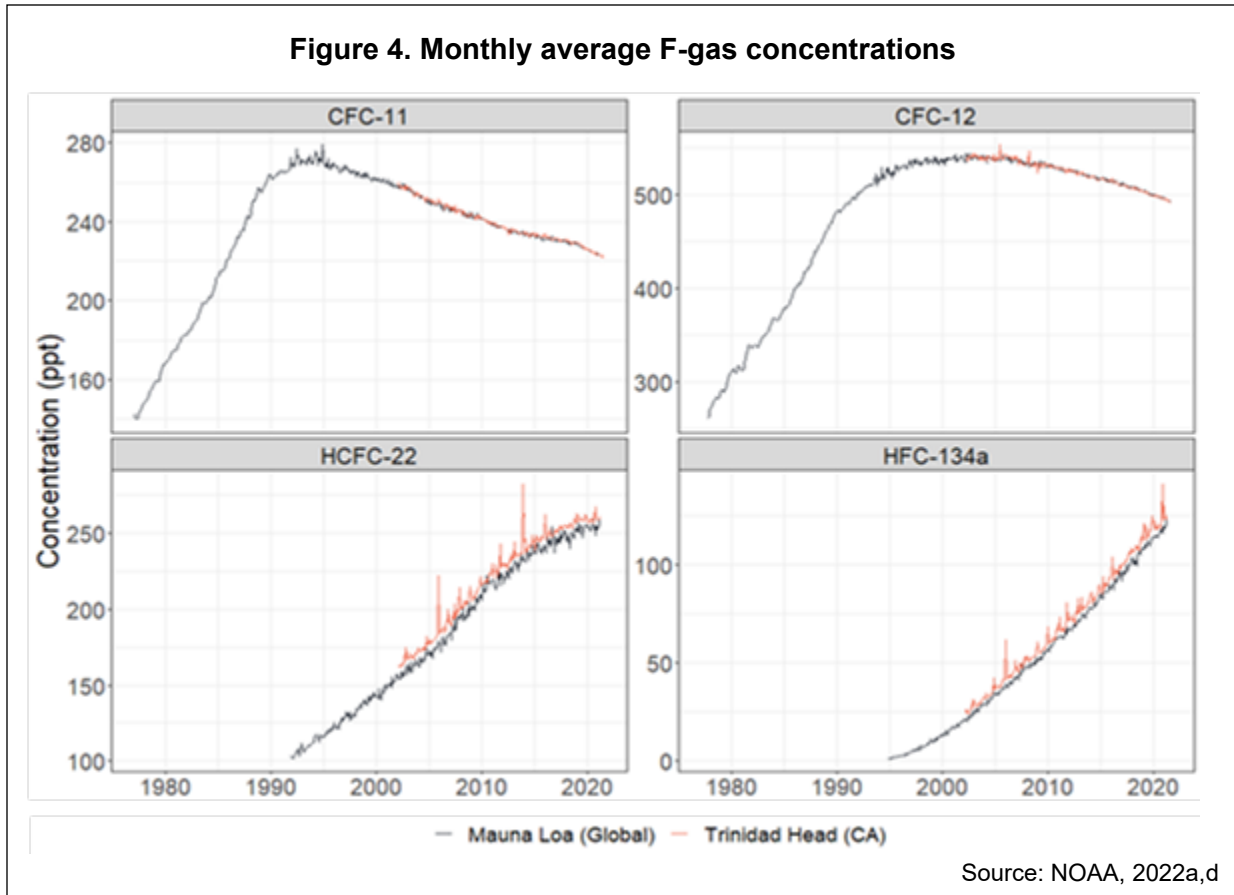**Figure 4. Monthly average F-gas concentrations**

Source: NOAA, 2022a,d

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 20th 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_2, 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
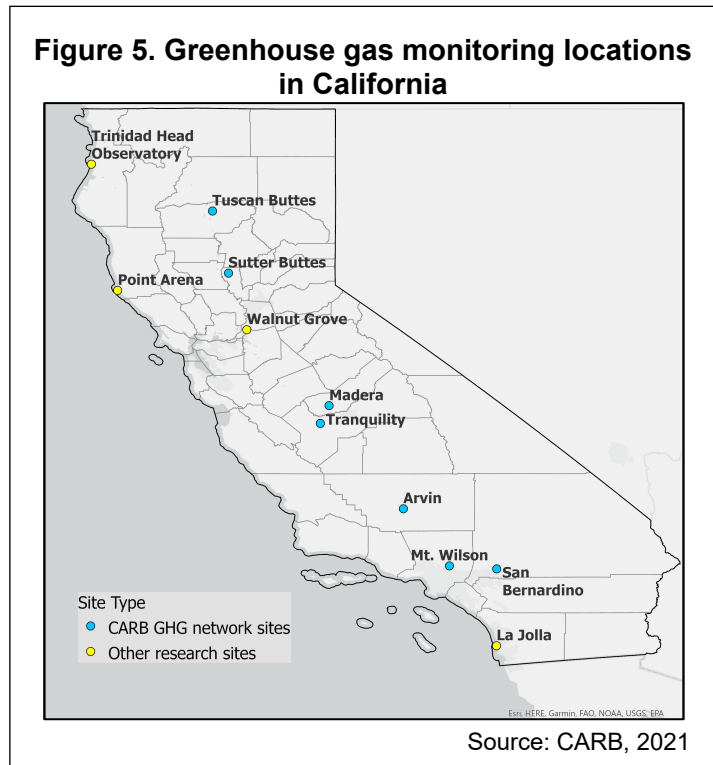
throughout the atmosphere and there is no latitudinal gradient in atmospheric CFC concentrations. Thus, Mauna Loa and Trinidad Head have nearly identical CFC levels.

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.
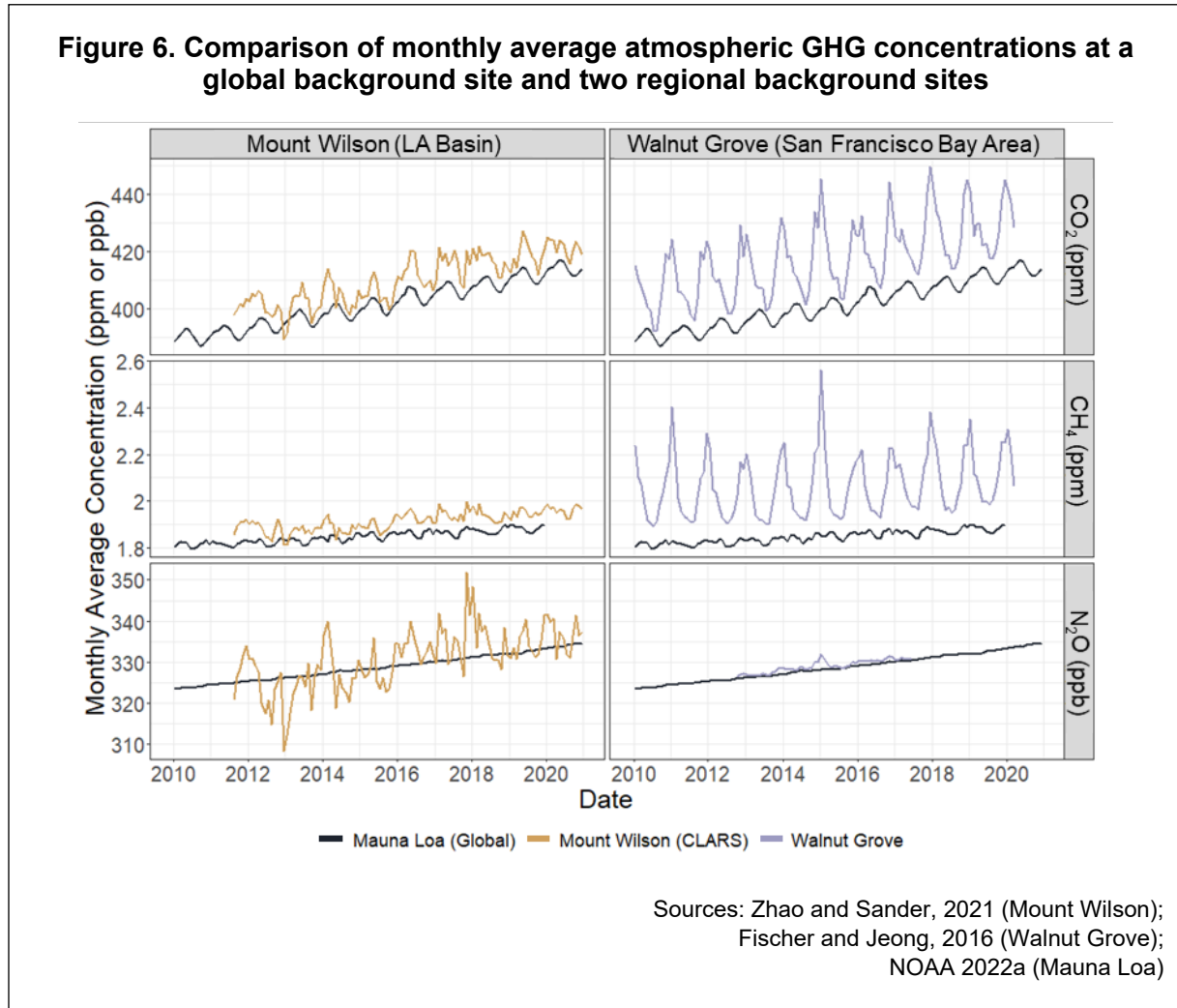
California has undertaken additional efforts to track the changes in ambient GHG concentrations at several monitoring sites located throughout the state. Figure 5 shows the seven GHG monitoring network sites operated by the California Air Resources Board (CARB), a research monitoring site operated by 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

Site Type
- CARB GHG network sites
- Other research sites

Esri, HERE, Garmin, FAO, NOAA, USGS, EPA

Source: CARB, 2021

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

Figure 6 shows monthly averaged CO_2, CH_4, and N_2O 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_2 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_2 concentration in the LA basin increased from roughly 400 ppm in 2011 to over 420 ppm by 2020. Similarly, the CO_2 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_2 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_4 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_2, larger inter- and intra-annual variability in CH_4 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_4 emission sources.

Annual N_2O 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_2O 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_2 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_2 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_2 levels were initiated by Charles D. Keeling in 1958 at Mauna Loa. For the first time, these measurements documented that atmospheric CO_2 levels were increasing globally. In the 1980s and the 1990s, it was recognized that greater coverage of CO_2 measurements was required to provide the basis for estimating the emission impacts of sources and sinks of atmospheric CO_2 over land as well as ocean regions. Since CO_2 remains in the atmosphere for many centuries, its atmospheric levels can continue to increase even if its emissions are significantly reduced.

Atmospheric CH_4, N_2O, 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_2 (GWP = 1). Despite a much shorter lifetime than that of CO_2, these can cause significant climate impact in the near term, and are called short-lived climate pollutants (SLCPs). For instance, CH_4 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_2O 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_2, CH_4, and N_2O 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_2, CH_4, N_2O, 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_2 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_2 concentration was estimated to be less than 280 ppm (WMO, 2016). During this period, the amount of CO_2 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_2 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_2 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_2 will continue to increase in the atmosphere even if annual CO_2 emissions are

substantially reduced from present levels. It should be noted that, while increasing levels of atmospheric CO_2 are affecting climate, changes in climate are likewise affecting the processes that lead to CO_2 uptake from, and release into, the atmosphere (IPCC, 2021). For example, warming temperatures increase plant photosynthesis and thus CO_2 removal from the atmosphere, and wildfires release carbon stored by plants back into the atmosphere.

Atmospheric CO_2 concentrations reflect regional, as well as seasonal and inter-annual influences. Due to its higher fossil fuel emissions, the Northern Hemisphere has higher CO_2 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_2 correspond to El Niño conditions, and lower-than-average increases correspond to La Niña conditions (IPCC, 2021).

Atmospheric CH_4 originates from both natural and anthropogenic sources. CH_4 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_4 by many of these sources is influenced by anaerobic fermentation processes and climate variables (notably temperature and moisture). Atmospheric removal of CH_4, on the other hand, is driven by oxidation processes, a process likewise affected by climate variables.

Atmospheric N_2O 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_2O emissions globally (US EPA, 2021). In California, N_2O 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_2O 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_2O from such fertilizers has been shown to vary based on their rate of application and watering events.

N_2O 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_2O is prevalent in the tail-pipe exhaust of motor vehicles when their engines and catalytic converters are operating at sub-optimal conditions. N_2O is also typically generated as a by-product of synthetic fertilizer and other synthetic nitrogen production processes. On the other hand, N_2O 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_2 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_2 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_2 and CH_4 continuously since September 2011 and N_2O 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_2. The Walnut Grove site is the first tall tower site in the world with continuous CH_4 measurements (under NOAA-ESRL's Global Monitoring Division).

Ambient CH_4 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_4 using a flame ionization detector (FID) integrated with a gas chromatograph (GC) system. LBNL and CARB network sites collect continuous air measurements of CH_4 using high-precision cavity ring-down spectroscopy (CRDS) with the same collection frequency and quality control protocols. CH_4 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_2O 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_2O. LBNL and CARB network sites use off-axis integrated cavity output spectroscopy to continuously measure N_2O concentrations. Quality control protocols similar to those applied for CH_4 and CO_2 measurements are instituted to obtain high-precision N_2O 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_2, CH_4, N_2O, 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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References:

Anderson B, Bartlett KB, Frolking S, Hayhoe K, Jenkins JC and Salas WA (2010). *Methane and Nitrous Oxide Emissions from Natural Sources. US Environmental Protection Agency*.

Archer D, Eby M, Brovkin V, Ridgwell A, Cao L, et al. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences* **37**(1): 117.

CARB (2017). California Air Resources Board. *Potential Impact of the Kigali Amendment on California HFC Emissions Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phase-down Agreement of October 15, 2016, in Kigali, Rwanda ("Kigali Amendment")*.

CARB (2020a). *California Air Resources Board. California Greenhouse Gas Emission Inventory*. Retrieved June 1, 2021.

CARB (2021b). *California Air Resources Board. Climate Change Programs*. Retrieved June 1, 2021.

Conway T, Lang P and Masarie K (2007). Atmospheric Carbon Dioxide Dry Air Mole Fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, 1968–2006, version: 2007-09-19. 2007. Retrieved December 20, 2016.

Conway T, Lang P and Masarie K (2011). *Atmospheric Carbon Dioxide Dry Air Mole Fractions from the NOAA/ESRL Carbon Cycle Global Cooperative Network*, 1968–2010; version 2011-06-21.

Cui YY, Vijayan A, Falk M, Hsu YK, Yin D, et al. (2019). A multiplatform inversion estimation of statewide and regional methane emissions in California during 2014-2016, Environmental Science & Technology **53**: 9636-9645

Fischer ML and Jeong S (2016). *Atmospheric Measurement and Inverse Modeling to Improve Greenhouse Gas Emission Estimates*. Prepared for the California Air Resources Board and the California Environmental Protection Agency. Lawrence Berkeley National Laboratory.

Frankenberg C, Meirink JF, van Weele M, Platt U and Wagner T (2005). Assessing methane emissions from global space-borne observations. *Science* **308**(5724): 1010-1014.

Fu D, Pongetti TJ, Blavier JFL, Crawford TJ, Manatt KS, et al. (2014). Near-infrared remote sensing of Los Angeles trace gas distributions from a mountaintop site. *Atmospheric Measurement Techniques*, **7**(3): 713-729

Gallagher G, Zhan T, Hsu Y-K, Gupta P, Pederson J, et al. (2014). High-global warming potential F-gas emissions in California: Comparison of ambient-based versus inventory-based emission estimates, and implications of refined estimates. *Environmental Science & Technology* **48**(2): 1084-1093.

Graham LA, Belisle SL and Rieger P (2009). Nitrous oxide emissions from light duty vehicles. *Atmospheric Environment* **43**(12): 2031-2044.

Hansen J, Kharecha P, Sato M, Masson-Delmotte V, Ackerman F, et al. (2013) Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature. *PLOS ONE* **8**(12): e81648.

Huai T, Durbin TD, Miller JW and Norbeck JM (2004). Estimates of the emission rates of nitrous oxide from light-duty vehicles using different chassis dynamometer test cycles. *Atmospheric Environment* **38**(38): 6621-6629.

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, et al. (Eds.)]. Cambridge University Press. In Press.

Keeling CD, Piper SC, Bacastow RB, Wahlen M, Whorf TP, et al. (2001). Exchanges of atmospheric CO_2 and $13CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000. *I. Global Aspects*. SIO Reference No. 01-06 (Revised from SIO Reference No. 00-21), June 2001. Available at

Molina MJ, Rowland FS, (1974). Stratospheric sink for chlorofluoromethanes: chlorine atom-catalyzed destruction of ozone. *Nature* 249: 810-812.

NOAA (2021a). National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division. Retrieved June 1, 2021.

NOAA (2021b). Carbon Cycle Trace Gas Measurement Details. National Oceanic and Atmospheric Administration, Earth System Research Laboratory. Retrieved April 1, 2021.

NOAA (2022a). Trends in Atmospheric Carbon Dioxide. National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division. Tans, P (NOAA/GML) and Keeling R (Scripps Institution of Oceanography). Retrieved June 29, 2022.

NOAA (2022b). Trends in Atmospheric Methane. National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division. Dlugokencky E (NOAA/GML). Retrieved June 29, 2022.

NOAA (2022c). Trends in Atmospheric Nitrous Oxide. National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division. Dlugokencky E (NOAA/GML). Retrieved June 29, 2022.

NOAA (2022d). CCGG Cooperative Air Sampling Network. National Oceanic and Atmospheric Administration, Earth System Research Laboratory. Retrieved April 1, 2021.

SIO (2022). Monthly atmospheric CO_2 concentrations (ppm) derived from flask air samples. La Jolla Pier, California. Scripps CO_2 Program, Scripps Institution of Oceanography. Retrieved March 25, 2022.

UNEP (2012). United Nations Environmental Programme. The Montreal Protocol: The Montreal Protocol on Substances that Deplete the Ozone Layer, Article 2A: CFCs. Retrieved June 1, 2021.

UNFCC (2016). United Nations Framework on Climate Change, Retrieved June 1, 2021.

US EPA (2021). Overview of Greenhouse Gases: Nitrous Oxide Emissions. Retrieved May 1, 2021.

WMO (2016). *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Using Global Observations through 2015*.

Wong KW, Pongetti TJ, Newman S, Kort EA, Duren R, et al. (2015). Mapping $CH_4:CO_2$ ratios in Los Angeles with CLARS-FTS from Mount Wilson, California. *Atmospheric Chemistry and Physics*, **15**: 241-252.

Zhao C, Andrews AE, Bianco L, Eluszkiewicz J, Hirsch A, et al. (2009). Atmospheric inverse estimates of methane emissions from Central California. *Journal of Geophysical Research: Atmospheres* **114**(D16).

Zhao, C and Sander, SP (2021). CARB Research Contract 17RD030, Quantifying Trends in Methane, Nitrous Oxide, and Carbon Monoxide Emissions in the Los Angeles Basin Using Remote Sensing Spectroscopy at CLARS.