

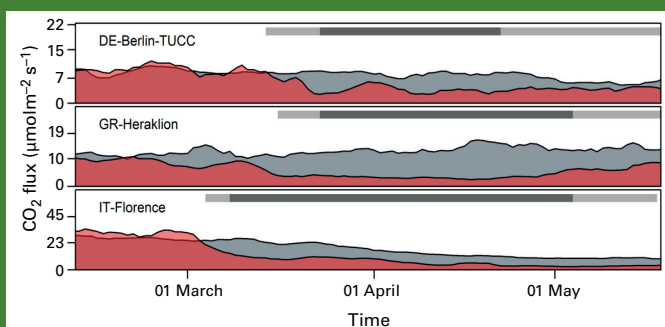


WMO GREENHOUSE GAS BULLETIN

The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2019

No. 16 | 23 November 2020

Can we see the impact of COVID-19 confinement measures on CO₂ levels in the atmosphere?



Average daily CO₂ emissions from 5 February to 6 May 2020 (red area) and average of the previous years during the same period (grey area) for three European cities. The dark grey horizontal bars cover periods of official lockdown, while the light grey bars indicate periods of partial lockdown or general restrictions (for example, school closures, reductions in personal contact, mobility constraints). Source: [6]

Humanity is experiencing a fundamental health and economic crisis related to COVID-19. The confinement measures broadly introduced earlier in 2020 and now reintroduced in many locations have had an impact on anthropogenic emissions of multiple constituents and resulted in changes in the chemical composition of the atmosphere. These changes have been especially pronounced in urban areas and are visible in traditional pollutants as well as in greenhouse gases. However, the reduction in anthropogenic emissions due to confinement measures will not have a discernible effect on global mean atmospheric CO₂ in 2020 as this reduction will be smaller than, or at most, similar in size to the natural year-to-year variability of atmospheric CO₂.

The global atmospheric CO₂ concentration represents the budget between the fluxes of CO₂ in and out of the atmosphere. CO₂ is a gas that is well mixed by turbulent mixing and atmospheric transport; it accumulates in the atmosphere over long timescales, and any non-zero emission leads to an increase in the atmospheric concentration. Anthropogenic emissions of CO₂ have been increasing globally since pre-industrial times (before 1750) and have risen by about 1% per year over the last decade [1]. This has resulted in an annual increase in the atmospheric CO₂ mole fraction⁽¹⁾ of between 2 and 3 ppm⁽²⁾ over the last ten years. This increase has been documented by the Global Atmosphere Watch (GAW) global network of surface stations, which can detect global changes of atmospheric CO₂ over a year within 0.1 ppm of precision. The year-to-year variability of about 1 ppm in the atmospheric growth rate is almost entirely due to variability in the uptake of CO₂ by ecosystems

and oceans (that together take up annually roughly half of human CO₂ emissions [2]). CO₂ originating from fossil fuel sources can be distinguished from CO₂ originating from biogenic sources using isotopic analysis, as was described in the previous Greenhouse Gas Bulletin.

The Global Carbon Project (GCP) [3] estimated that during the most intense period of forced confinement in early 2020, daily global CO₂ emissions may have been reduced by up to 17% compared to the mean level of daily CO₂ emissions in 2019. As the duration and severity of the confinement measures remain unclear, it is very difficult to predict the total annual reduction in CO₂ emissions for 2020; however, preliminary estimates anticipate a reduction of between 4.2% and 7.5% compared to 2019 levels. At the global scale, an emission reduction of this magnitude will not cause atmospheric CO₂ levels to decrease; they will merely increase at a slightly reduced rate, resulting in an anticipated annual atmospheric CO₂ concentration that is 0.08 ppm–0.23 ppm lower than the anticipated CO₂ concentration if no pandemic had occurred. This falls well within the 1 ppm natural inter-annual variability and means that in the short-term, the impact of COVID-19 confinement measures cannot be distinguished from natural year-to-year variability. A similar conclusion was reached by Carbon Brief [4] and the Integrated Carbon Observation System (ICOS) [5].

Determining changes in the fossil fuel signal given the high natural atmospheric variability of CO₂ requires a long time series in order to generate robust statistics, as well as complex data modelling. Several approaches can be used to make this determination. One such approach, the WMO Integrated Global Greenhouse Gas Information System (IG³IS), utilizes atmospheric observations and modelling. Another approach, adopted by ICOS [6], directly measures CO₂ emissions within cities. A recent study by ICOS detected reductions in CO₂ emissions of up to 75% in the city centres of Basel, Berlin, Florence, Helsinki, Heraklion, London and Pesaro using techniques that directly measure vertical exchange fluxes within a circumference of several kilometres from the measurement point (see the figure).

Only when net fossil fuel emissions of CO₂ approach zero will the net uptake by ecosystems and oceans start to reduce CO₂ levels in the atmosphere. Even then, most of the CO₂ already added to the atmosphere will remain there for several centuries, continuing to warm our climate. In addition, the Earth climate system has a lag time of several decades due to buffering of the excess heat by the oceans, so the sooner we reduce our emissions, the less likely we are to overshoot the warming threshold the world agreed to in the Paris Agreement.

Executive summary

The latest analysis of observations from the WMO Global Atmosphere Watch (GAW) in-situ observational network shows that globally averaged surface mole fractions⁽¹⁾ for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) reached new highs in 2019, with CO₂ at 410.5±0.2 ppm⁽²⁾, CH₄ at 1877±2 ppb⁽³⁾ and N₂O at 332.0±0.1 ppb. These values constitute, respectively, 148%, 260% and 123% of pre-industrial levels. The increase in CO₂ from 2018 to 2019 was larger than that observed from 2017 to 2018 and larger than the average annual growth rate over the last decade. For CH₄, the increase from 2018 to 2019 was slightly lower than that observed from 2017 to 2018 but still higher than the average annual growth rate over the last decade. For N₂O, the increase from 2018 to 2019 was lower than that observed from 2017 to 2018 and practically equal to the average annual growth rate over the past 10 years. The National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (AGGI) [7] shows that from 1990 to 2019, radiative forcing by long-lived greenhouse gases (LLGHGs) increased by 45%, with CO₂ accounting for about 80% of this increase.

Overview of observations from the GAW in-situ observational network for 2019

This sixteenth annual WMO Greenhouse Gas Bulletin reports atmospheric abundances and rates of change of the most important LLGHGs – carbon dioxide, methane and nitrous oxide – and provides a summary of the contributions of other greenhouse gases (GHGs). CO₂, CH₄ and N₂O, together with CFC-12 and CFC-11, account for approximately 96%⁽⁴⁾ [7] of radiative forcing due to LLGHGs (Figure 1).

The WMO Global Atmosphere Watch Programme (<https://community.wmo.int/activity-areas/gaw>) coordinates systematic observations and analyses of greenhouse gases and other trace species. Sites where greenhouse gases have been measured in the last decade are shown in Figure 2. Measurement data are reported by participating countries and archived and distributed by the World Data Centre for Greenhouse Gases (WDCGG) at the Japan Meteorological Agency. WDCGG plays an important role in data management within the GAW Programme and celebrates its 30th anniversary this year.

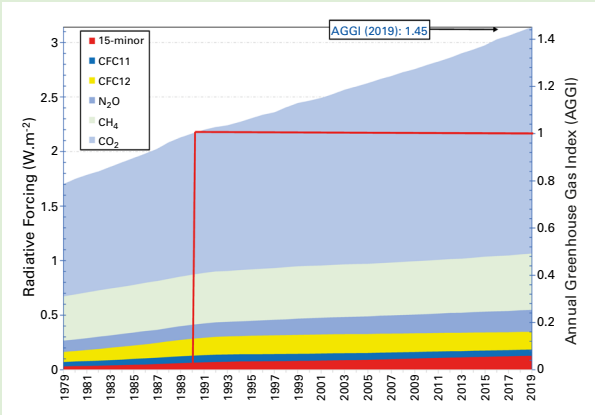


Figure 1. Atmospheric radiative forcing, relative to 1750, by LLGHGs corresponding to the 2019 update of the NOAA AGGI [7].

Table 1. Global annual surface mean abundances (2019) and trends of key greenhouse gases from the GAW in-situ observational network for GHGs. Units are dry-air mole fractions, and uncertainties are 68% confidence limits [10]. The averaging method is described in GAW Report No. 184 [9].

	CO ₂	CH ₄	N ₂ O
2019 global mean abundance	410.5±0.2 ppm	1877±2 ppb	332.0±0.1 ppb
2019 abundance relative to 1750 ^a	148%	260%	123%
2018–2019 absolute increase	2.6 ppm	8 ppb	0.9 ppb
2018–2019 relative increase	0.64%	0.43%	0.27%
Mean annual absolute increase over the last 10 years	2.37 ppm yr ⁻¹	7.3 ppb yr ⁻¹	0.96 ppb yr ⁻¹

^a Assuming a pre-industrial mole fraction of 278 ppm for CO₂, 722 ppb for CH₄ and 270 ppb for N₂O. The number of stations used for the analyses was 133 for CO₂, 134 for CH₄ and 100 for N₂O

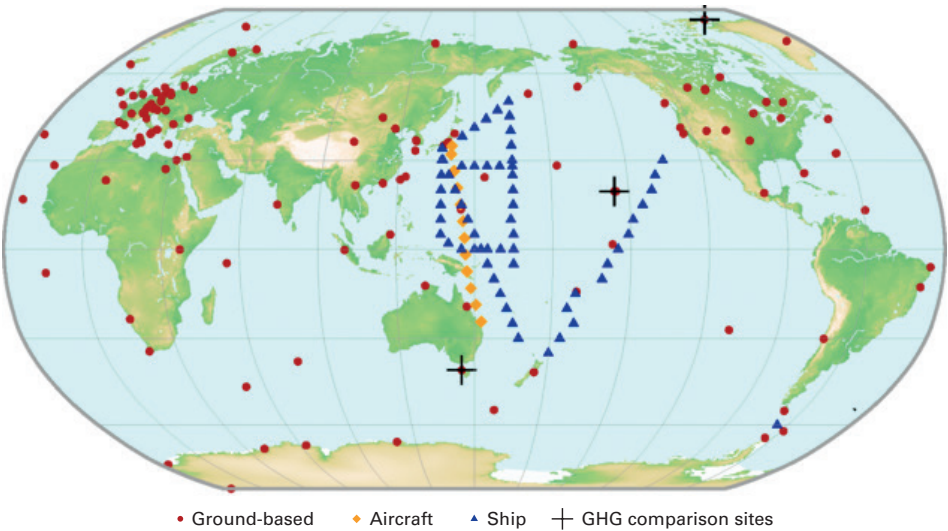


Figure 2. The GAW global network for carbon dioxide in the last decade. The network for methane is similar.

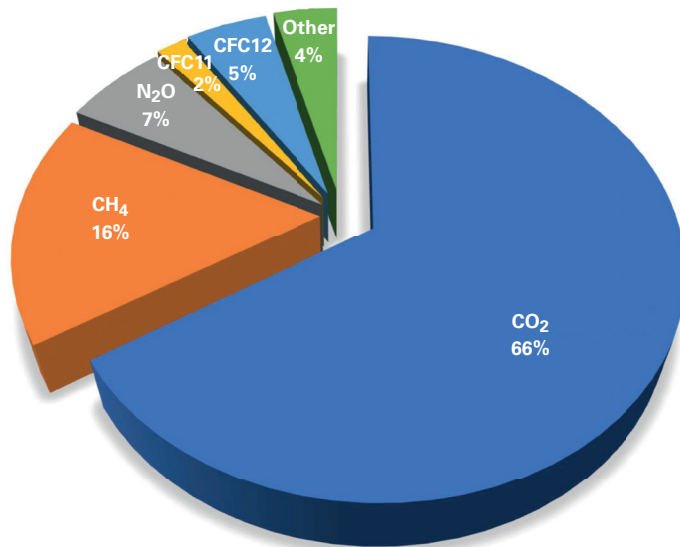


Figure 3. Contributions of the most important long-lived greenhouse gases to the increase in global radiative forcing from the pre-industrial era to 2019 [7]

The results reported here by WMO WDCGG for the global average and growth rate are slightly different from the results reported by NOAA for the same years [8] due to differences in the stations used and the averaging procedure, as well as a slight difference in the time period for which the numbers are representative. WMO WDCGG follows the procedure described in detail in GAW Report No. 184 [9].

Table 1 provides the globally averaged atmospheric abundances of the three major LLGHGs in 2019 and the changes in their abundances since 2018 and 1750. Data from mobile stations (blue triangles and orange diamonds in Figure 2), with the exception of data provided by NOAA sampling in the eastern Pacific, are not used for this global analysis.

The three GHGs shown in Table 1 are closely linked to anthropogenic activities and interact strongly with the biosphere and the oceans. Predicting the evolution of the atmospheric content of GHGs requires a quantitative understanding of their many sources, sinks and chemical transformations in the atmosphere. Observations from GAW provide invaluable constraints on the budgets of these and other LLGHGs, and they are used to improve emission estimates and evaluate satellite retrievals of LLGHG column averages. IG³IS provides further insights on the sources and sinks of GHGs at the national and sub-national level (<https://ig3is.wmo.int>).

The NOAA AGGI measures the increase in total radiative forcing due to all LLGHGs since 1990 [7]. The AGGI reached 1.45 in 2019, representing a 45% increase in total radiative forcing⁽⁴⁾ from 1990 to 2019 and a 1.8% increase from 2018 to 2019 (Figure 1). The total radiative forcing by all LLGHGs in 2019 (3.14 W.m⁻²) corresponds to an equivalent CO₂ mole fraction of 500 ppm [7]. The relative contributions of the most important long-lived greenhouse gases to the increase in global radiative forcing from the pre-industrial era to 2019 are presented in Figure 3.

Carbon Dioxide (CO₂)

Carbon dioxide is the single most important anthropogenic greenhouse gas in the atmosphere, accounting for approximately 66%⁽⁴⁾ of the radiative forcing by LLGHGs. It is responsible for

about 82%⁽⁴⁾ of the increase in radiative forcing over the past decade and also about 82% of the increase over the past five years. The pre-industrial level of 278 ppm represented a balance of fluxes among the atmosphere, the oceans and the land biosphere. The globally averaged CO₂ mole fraction in 2019 was 410.5±0.2 ppm (Figure 4). The increase in annual means from 2018 to 2019, 2.6 ppm, was higher than the increase from 2017 to 2018 and higher than the average annual growth rate for the past decade (2.37 ppm yr⁻¹).

Atmospheric CO₂ reached 148% of the pre-industrial level in 2019, primarily because of emissions from the combustion of fossil fuels and cement production (fossil fuel CO₂ emissions were projected to reach 36.7±2 GtCO₂⁽⁵⁾ in 2019 [1]), deforestation and other land-use change (5.5 GtCO₂ yr⁻¹ average for 2009–2018). Of the total emissions from human activities during the 2009–2018 period, about 44% accumulated in the atmosphere, 23% in the ocean and 29% on land, with the unattributed budget imbalance being 4% [2]. The portion of CO₂ emitted by fossil fuel combustion that remains in the atmosphere (airborne fraction), varies inter-annually due to

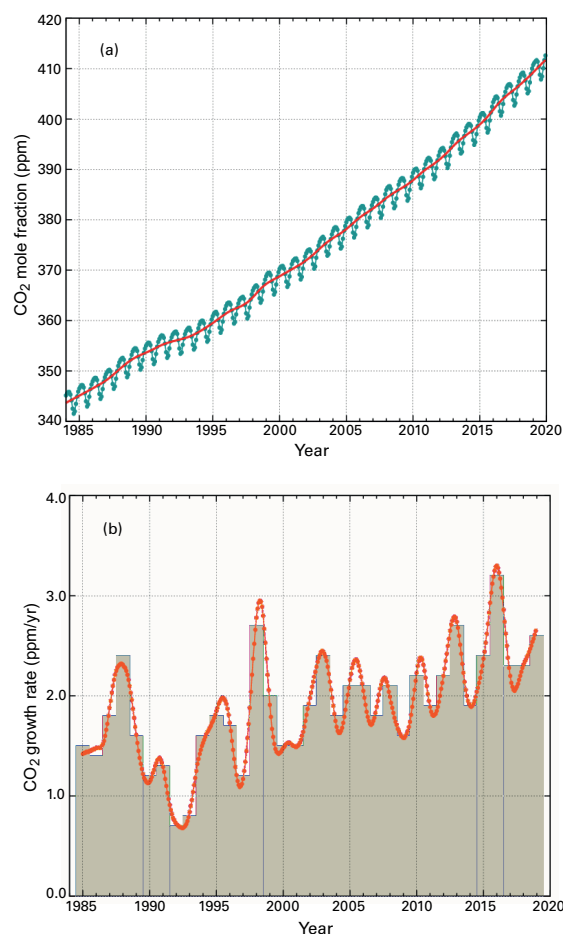


Figure 4. Globally averaged CO₂ mole fraction (a) and its growth rate (b) from 1984 to 2019. Increases in successive annual means are shown as the shaded columns in (b). The red line in (a) is the monthly mean with the seasonal variation removed; the blue dots and blue line in (a) depict the monthly averages. Observations from 133 stations were used for this analysis.

Local methane emission monitoring in support of the climate goals of the Paris Agreement

Sander Houweling

The global methane (CH_4) increase of 8 ppb per year in 2019, reported in this Bulletin, continues the trend of the past decade of methane increasing by 5–10 ppb per year. In its most recent assessment, the Global Carbon Project (GCP) [11] estimated the global emission of methane to be $576 \text{ Tg CH}_4 \text{ yr}^{-1}$ for the period 2008–2017. This corresponds to a mean annual total emission that is 29 Tg yr^{-1} larger than the estimate for the previous decade. These numbers were obtained from an inverse modelling inter-comparison using surface measurements from GAW and satellite measurements from the Japanese Greenhouse gas Observing SATellite (GOSAT). Inversions based on these data agree that the tropics and South-East Asia contribute most to the increase. However, it is difficult to provide further details that are robust across the inversion ensemble and with respect to the relative importance of changes in anthropogenic and natural sources. Indeed, the GCP assessment does not further constrain the wide range of scenarios and possible explanations that have been proposed in earlier studies for the renewed increase of CH_4 since 2007 (see, for example, [15]–[18]).

The observed trend in $\delta^{13}\text{C}-\text{CH}_4$, which was not used in the GCP assessment, is explained by a combined increase in microbial and fossil emissions [18]. This trend points to the likely scenario that the methane increase is largely driven by the growing demand for energy and food. This is broadly consistent with the EDGARv5 emission inventory [19], in which anthropogenic sources accounted for an increase of $30 \text{ Tg CH}_4 \text{ yr}^{-1}$ in the period 2008–2015, which is more than enough to explain the observed increase.

Figure 5 shows the increase in methane, and the acceleration of that increase since 2014, compared to the representative concentration pathways (RCPs), also known as climate scenarios, of the 5th Assessment Report (AR5) of the International Panel on Climate Change (IPCC). Methane follows a trajectory that is in between RCP 6 and RCP 8.5, the strongest warming scenarios. Several studies

have pointed to the short-term climate benefits and cost-effectiveness of mitigating methane emissions [20], [21]. However, Figure 5 shows that international efforts to achieve the goals of the Paris Agreement have so far not focused on mitigating methane emissions.

Figure 6 shows a natural gas leak in western Turkmenistan that was first detected by the GHGSat satellite in 2019 and later confirmed by Sentinel 5p TROPOMI [22]. A plume of total column methane was visible and changed direction between subsequent satellite overpasses in a manner consistent with the local wind direction. Despite the challenge of measuring methane from space with sufficient accuracy, there was little doubt that these signals were real. The emission was estimated at $142 \pm 34 \text{ ktCH}_4 \text{ yr}^{-1}$, which is a large leak (about 6 m^3 of methane per second), but one that had nevertheless gone unnoticed for several years. The TROPOMI data that have been collected so far show several such natural gas leaks worldwide (see, for example, [23], [24]). Satellites with more sensitive sensors (for example, the MethaneSat satellite) are planned to be launched in the coming years, with GHGSat's Iris satellite already having been launched in September of this year. The sensors on these satellites will potentially enable more leaks to be detected with a higher degree of precision.

Substantial methodological development is still needed to improve satellite-derived emission estimates, for which accurate measurements on the ground are indispensable. However, with the current capabilities, an important new contribution to regional emission monitoring can already be made. This is a notable example of a new development that responds directly to the IG³IS objective of reducing methane emissions in the oil and gas sector. IG³IS is ideally positioned to bring international scientists and end users together in order to ensure that new regional emission monitoring capabilities will be used for the climate action that is urgently needed to make the Paris Agreement a success.

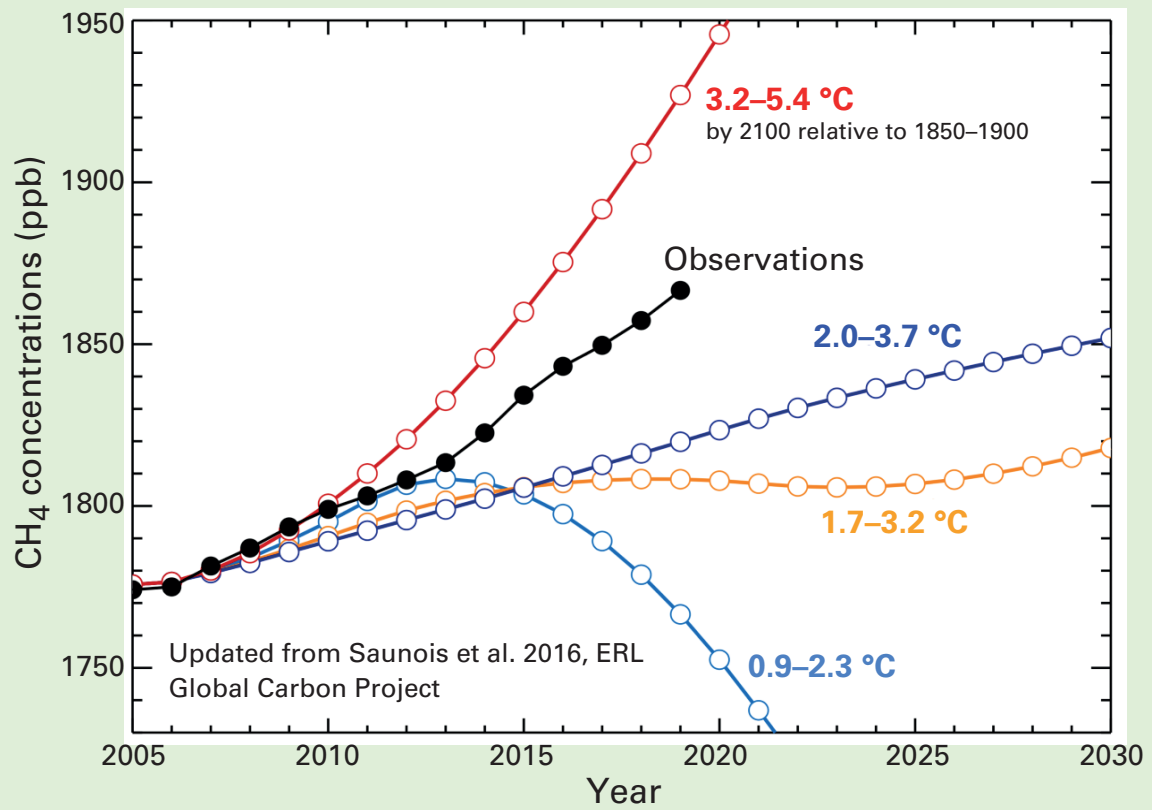


Figure 5. The observed global increase of CH₄ compared to IPCC AR5 RCP scenarios [11]

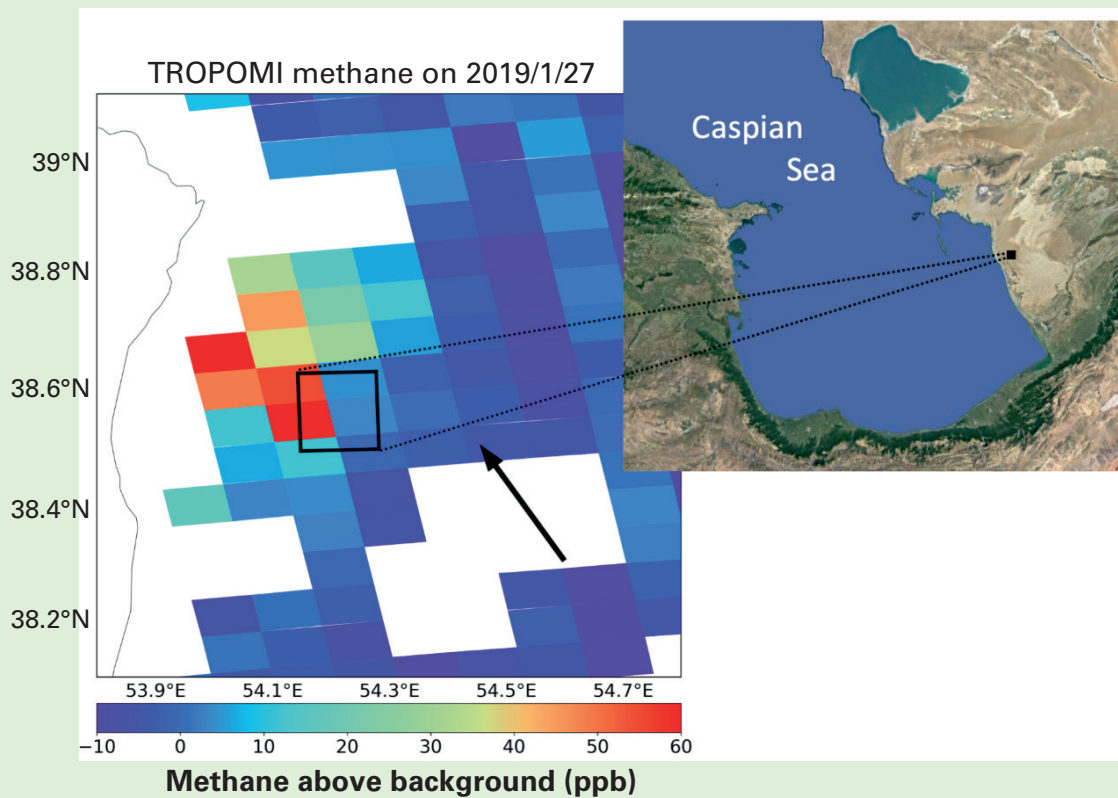


Figure 6. TROPOMI-observed methane emissions from oil and gas production in western Turkmenistan [22]

the high natural variability of CO₂ sinks without a confirmed global trend.

Methane (CH₄)

Methane accounts for about 16%⁽⁴⁾ of the radiative forcing by LLGHGs. Approximately 40% of methane is emitted into the atmosphere by natural sources (for example, wetlands and termites), and about 60% comes from anthropogenic sources (for example, ruminants, rice agriculture, fossil fuel exploitation, landfills and biomass burning) [11]. Globally averaged CH₄ calculated from in-situ observations reached a new high of 1877±2 ppb in 2019, an increase of 8 ppb with respect to the previous year (Figure 7). This increase is lower than the increase of 9 ppb in the period 2017–2018 but still slightly higher than the average annual increase over the past decade. The mean annual increase of CH₄ decreased from approximately 12 ppb yr⁻¹ during the late 1980s to near zero during 1999–2006. Since 2007, atmospheric CH₄ has been increasing, reaching 260% of the pre-industrial level (approximately 722 ppb) due to increased emissions from anthropogenic sources. Studies using GAW CH₄ measurements indicate that increased CH₄ emissions from wetlands in the tropics and from anthropogenic sources at the mid-latitudes of the northern hemisphere are the likely causes of this recent increase.

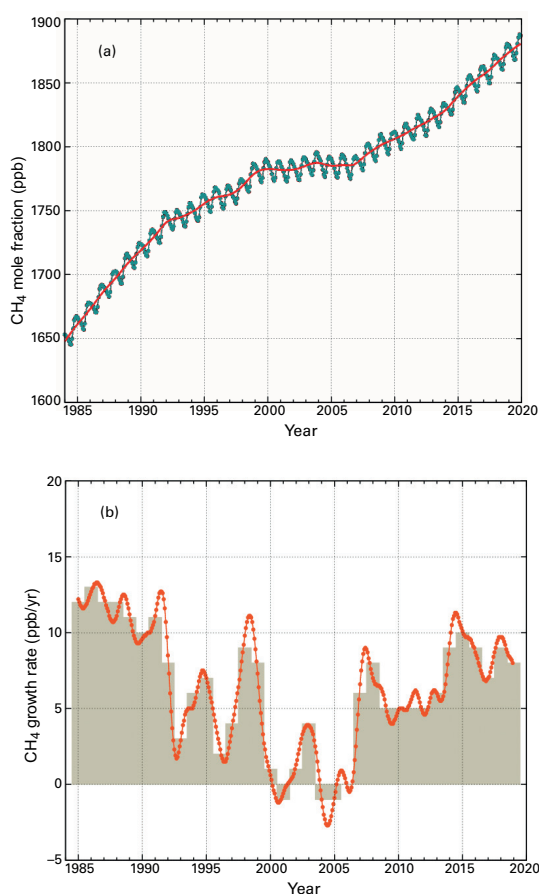


Figure 7. Globally averaged CH₄ mole fraction (a) and its growth rate (b) from 1984 to 2019. Increases in successive annual means are shown as the shaded columns in (b). The red line in (a) is the monthly mean with the seasonal variation removed; the blue dots and blue line in (a) depict the monthly averages. Observations from 134 stations were used for this analysis.

Nitrous Oxide (N₂O)

Nitrous oxide accounts for about 7%⁽⁴⁾ of the radiative forcing by LLGHGs. It is the third most important individual contributor to the combined forcing. N₂O is emitted into the atmosphere from both natural sources (approximately 60%) and anthropogenic sources (approximately 40%), including oceans, soils, biomass burning, fertilizer use, and various industrial processes. The globally averaged N₂O mole fraction in 2019 reached 332.0±0.1 ppb, which is an increase of 0.9 ppb with respect to the previous year (Figure 8) and 123% of the pre-industrial level (270 ppb). The annual increase from 2018 to 2019 was lower than the increase from 2017 to 2018 and almost equal to the mean growth rate over the past 10 years (0.96 ppb yr⁻¹). Global human-induced N₂O emissions, which are dominated by nitrogen additions to croplands, increased by 30% over the past four decades to 7.3 (range: 4.2–11.4) teragrams of nitrogen per year. This increase was mainly responsible for the growth in the atmospheric burden of N₂O [12].

Other greenhouse gases

The stratospheric ozone-depleting chlorofluorocarbons (CFCs), which are regulated by the Montreal Protocol, together with minor halogenated gases, account for approximately 11%⁽⁴⁾ of

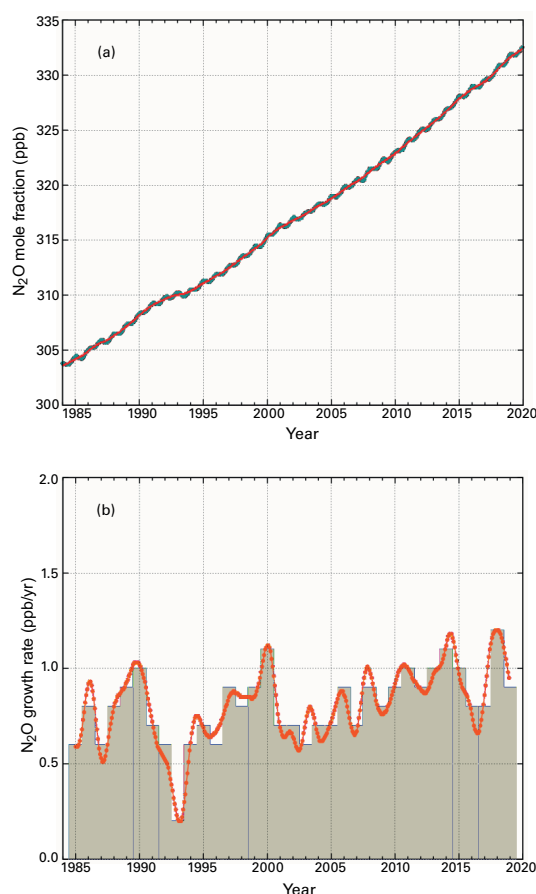


Figure 8. Globally averaged N₂O mole fraction (a) and its growth rate (b) from 1984 to 2019. Increases in successive annual means are shown as the shaded columns in (b). The red line in (a) is the monthly mean with the seasonal variation removed; in this plot, the red line overlaps the blue dots and blue line that depict the monthly averages. Observations from 100 stations were used for this analysis.

the radiative forcing by LLGHGs. While CFCs and most halons are decreasing, some hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which are also potent greenhouse gases, are increasing at relatively rapid rates, although they are still low in abundance (at ppt⁽⁶⁾ levels). Although at a similarly low abundance, sulfur hexafluoride (SF₆) is an extremely potent LLGHG. It is produced by the chemical industry, mainly as an electrical insulator in power distribution equipment. Its current mole fraction is more than twice the level observed in the mid-1990s (Figure 9a).

This Bulletin primarily addresses long-lived greenhouse gases. Relatively short-lived tropospheric ozone has a radiative forcing comparable to that of the halocarbons [13]. Many other pollutants, such as carbon monoxide, nitrogen oxides and volatile organic compounds, although not referred to as greenhouse gases, have small direct or indirect effects on radiative forcing. Aerosols (suspended particulate matter) are short-lived substances that alter the radiation budget. All the gases mentioned in this Bulletin, as well as aerosols, are included in the observational programme of GAW, with support from WMO Member countries and contributing networks.

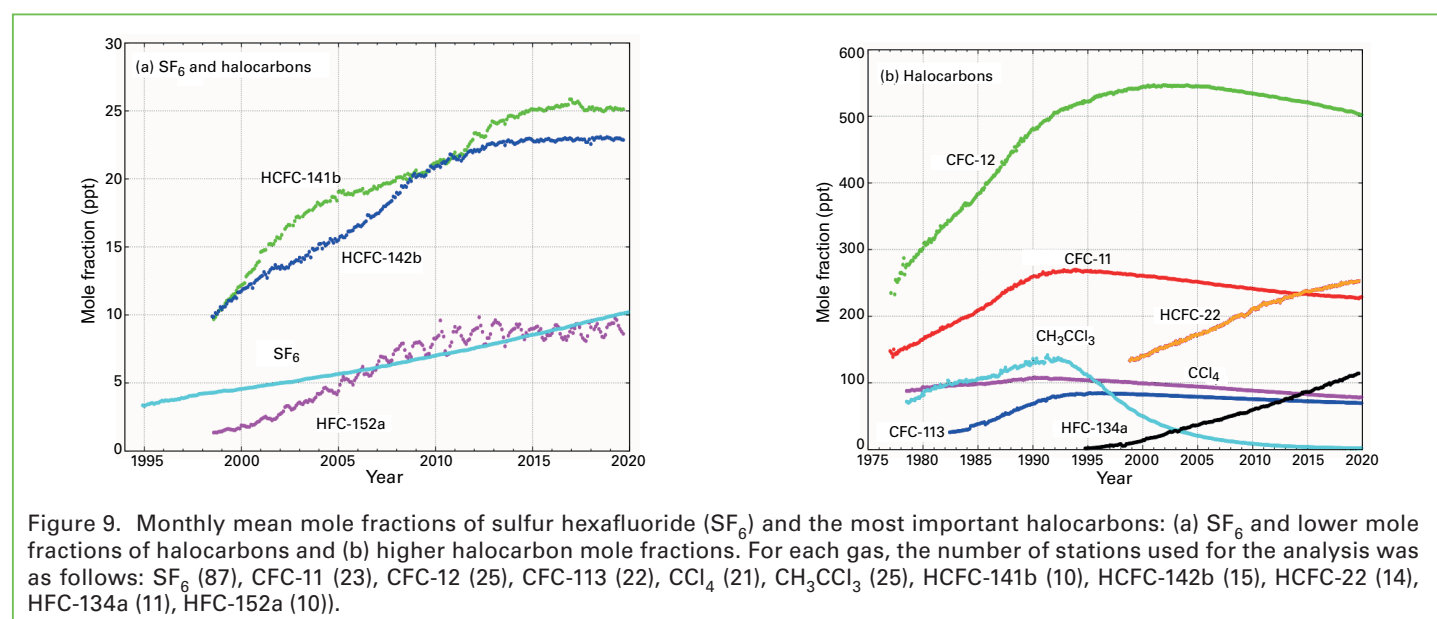
Acknowledgements and links

Fifty-five WMO Members contributed CO₂ and other greenhouse gas data to the GAW WDCGG. Approximately 40% of the measurement records submitted to WDCGG were obtained at sites of the NOAA Earth System Research Laboratory cooperative air-sampling network. For other networks and stations, see GAW Report No. 255 [14]. The Advanced Global Atmospheric Gases Experiment also contributed observations to this Bulletin. The GAW observational stations that contributed data to this Bulletin, shown in Figure 2, are included in the list of contributors on the WDCGG web page (<https://gaw.kishou.go.jp/>). They are also described in the GAW Station Information System, GAWSIS (<http://gawsis.meteoswiss.ch>), supported by MeteoSwiss, Switzerland.

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Notes:

- (1) Mole fraction = the preferred expression for the abundance (concentration) of a mixture of gases or fluids. In atmospheric chemistry, the mole fraction is used to express the concentration as the number of moles of a compound per mole of dry air.
- (2) ppm = the number of molecules of the gas per million (10⁶) molecules of dry air
- (3) ppb = the number of molecules of the gas per billion (10⁹) molecules of dry air
- (4) This percentage is calculated as the relative contribution of the mentioned gas(es) to the increase in global radiative forcing caused by all long-lived greenhouse gases since 1750.
- (5) 1 GtCO₂ = 1 billion (10⁹) metric tons of carbon dioxide
- (6) ppt = the number of molecules of the gas per trillion (10¹²) molecules of dry air

Selected greenhouse gas observatories

Many GAW stations have been established in very remote locations around the world. The confinement measures related to COVID-19 have created logistical problems due to this remoteness and the corresponding travel and transport restrictions. The challenges facing two stations located on remote islands in the Southern and Pacific Oceans are described below.

American Samoa (SMO)



Photo: NOAA ESRL

NOAA's American Samoa Atmospheric Baseline Observatory (SMO) is located in the middle of the South Pacific, about midway between Hawaii and New Zealand. It is characterized by year-round warmth and humidity, lush green mountains, and strong Samoan culture. The observatory is situated on the north-eastern tip of Tutuila Island, American Samoa, at Cape Matatula.

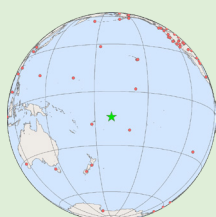
As the COVID-19 pandemic unfolded in spring 2020, American Samoa instituted strict travel restrictions including, for a time, the complete suspension of cargo flights to try to prevent the island's health institutes from being overwhelmed by an outbreak. The cargo and personnel travel restrictions prevented SMO from being resupplied with critical calibration gases, flasks and other essential materials and postponed a planned update to the CO₂ in-situ analysis system. Contingency plans were made to shutter the station and evacuate personnel in the event that the pandemic became a worst-case scenario situation on the island. In addition, the travel restrictions threatened to delay the scheduled annual station chief rotation, which typically includes a 2–3 week overlap for extensive in-person training. In the end, the new station chief was able to get to the island on a Department of Defense (DOD) humanitarian aid flight, and personnel were able to complete the full turnover before the outgoing station chief departed on another DOD flight. Travel restrictions remain in place, but luckily, the situation in American Samoa has not yet become a worst-case scenario, and all critical measurements and sampling at SMO have continued throughout the pandemic.

Location

Country: American Samoa
Latitude: 14.2474° South
Longitude: 170.5644° West
Elevation: 42.00 masl
Time zone: Local time = UTC – 11



Photo: P. Roberts



Macquarie Island (MQA)



Photo: Barry Becker

Macquarie Island is a subantarctic island located in the Southern Ocean, approximately halfway between Australia and Antarctica. "Macca", as it is commonly known, is a World Heritage site managed by the Tasmanian Parks and Wildlife Service. At the northern end of the island, the Australian Antarctic Division (AAD) has operated a research station which, for thirty years, has supported diverse scientific research and long-term monitoring programmes ranging from the conservation of significant populations of seabirds and seals to atmospheric composition measurements for the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Along with AAD, the Australian Bureau of Meteorology (BoM), the Australian Nuclear Science and Technology Organisation (ANSTO), the University of Heidelberg, Germany and GNS, New Zealand are all key collaborators in CSIRO's long-term atmospheric composition monitoring programme.

To ensure the safety of the very isolated staff wintering at Macca from the COVID-19 virus, strict quarantine protocols are in place for a single annual changeover of staff this (austral) summer. Training of BoM staff to support atmospheric flask sampling of CO₂, CH₄, N₂O, CO, H₂, δ¹³C-CO₂ and Δ¹⁴C-CO₂ and to collect in-situ measurements of CO₂, CH₄ and ²²²Rn has occurred virtually this year, and there will be no accompanying scientists visiting the island in the near future to undertake routine maintenance. Nevertheless, with the dedication of the wintering staff, sampling and in-situ measurements will continue throughout 2021 at this important southern hemisphere site.

Location

Country: Australia
Latitude: 54.4985° South
Longitude: 158.9385° East
Elevation: 16.00 masl
Time zone: Local time = UTC + 10



Photo: Vicki Heinrich

