Mauna Loa carbon dioxide forecast for 2024: Atmospheric CO_2 rise predicted to exceed IPCC 1.5°C scenarios

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The build-up of atmospheric carbon dioxide concentration between 2023 and 2024 is forecast to be faster than that required to track IPCC scenarios that limit global warming to 1.5°C. The ongoing CO_2 rise is mainly driven by fossil fuel burning and land use change, with an additional impact this year from the current El Niño causing a temporary weakening of tropical land carbon sinks. Even without the additional effect of El Niño, the annual CO_2 rise would be at the very limits of compatibility with the IPCC's 1.5°C scenarios.

We forecast the annual average CO_2 concentration at Mauna Loa, Hawaii to be 2.84 ± 0.54 parts per million (ppm) higher in 2024 than in 2023. As a result, we forecast the 2024 annual average CO_2 concentration at Mauna Loa to be 423.6 ± 0.5 ppm (Figure 1). This will continue the ongoing rising trend in CO_2 seen in the long-term record of measurements from the Mauna Loa observatory in Hawaii that date back to 1958 (also known as the Keeling Curve). The size of the annual CO_2 rise has generally been increasing but with substantial variation from year-to-year, with the forecast increase for 2024 being relatively large (Figure 2). The Mauna Loa record is a good guide to rise in global average CO_2 concentration, which we therefore expect to increase by a similar amount.

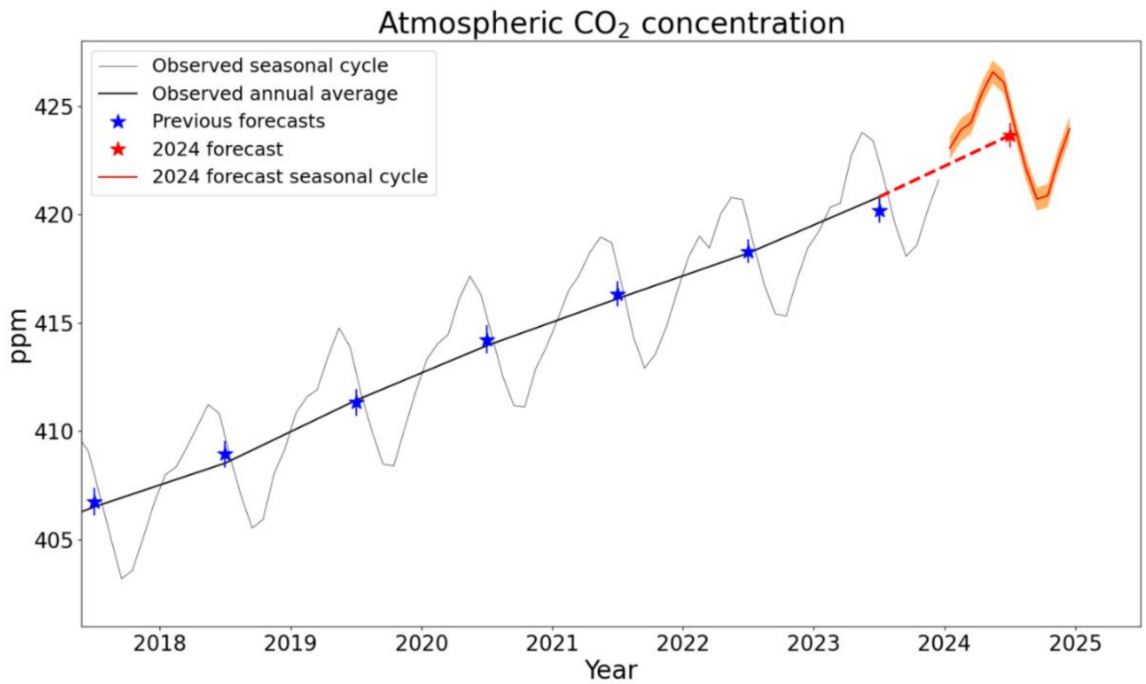

Figure 1. *Forecast CO_2 concentrations at the Mauna Loa observatory, showing monthly (red curve) and annual (red star) values. The orange band and vertical red line shows the forecast uncertainty ranges. The thin and thick black curves show the observed monthly and annual average concentrations respectively. Blue stars and blue lines show previous forecast annual averages and their uncertainties, with the 2020 value being the updated 2020 forecast issued followed the reduction in global CO_2 emissions due to the Covid-19 pandemic. Observed data is from the Scripps Institution of Oceanography, UC San Diego.*

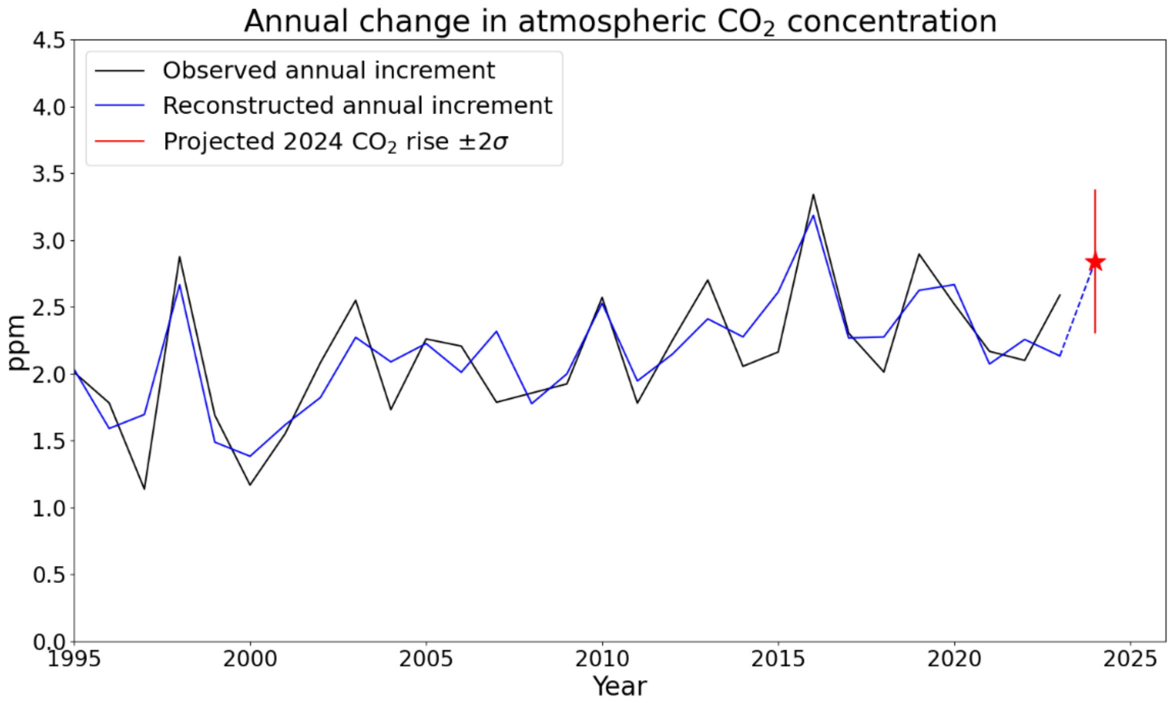

Figure 2. *Annual increments in CO_2 concentration at the Mauna Loa observatory from observations (black) and the 2024 forecast (red star). The forecast uncertainty range (red line) is ± 2 standard deviations. The blue line shows statistical reconstructions of past annual CO_2 increments using the same method as used in the forecast. Observations are from the Scripps Institution of Oceanography, UC San Diego.*

Contributions of anthropogenic emissions and varying natural carbon sinks to the CO_2 rise

Long-term increases in observed CO_2 are entirely the result of human-caused emissions of carbon dioxide into the atmosphere – more than enough CO_2 has been emitted by fossil fuel burning, cement production and deforestation to account for the increase measured in the atmosphere. Although CO_2 concentrations have now increased by over 50% since the industrial revolution, this increase would have been almost twice as large if some CO_2 had not been removed from the atmosphere through being absorbed by plants and the oceans.

These natural sinks of carbon vary in strength from year to year due to short-term fluctuations in climate, principally through El Niño Southern Oscillation (ENSO) cycles in the Tropical Pacific Ocean. This means that although emissions are increasing relatively smoothly, the rate of CO_2 increase in the atmosphere shows more variability due to the varying strength of natural carbon sinks. El Niño conditions typically lead to a faster annual CO_2 rise, while La Niña conditions typically lead to a slower annual CO_2 rise. The Met Office CO_2 forecast takes account of both anthropogenic emissions and the impacts of ENSO-related climate variability on natural carbon sinks, accounting for the latter using the observed correlation between the annual CO_2 rise and sea surface temperatures (SSTs) in the equatorial Pacific Ocean (Figure 3).

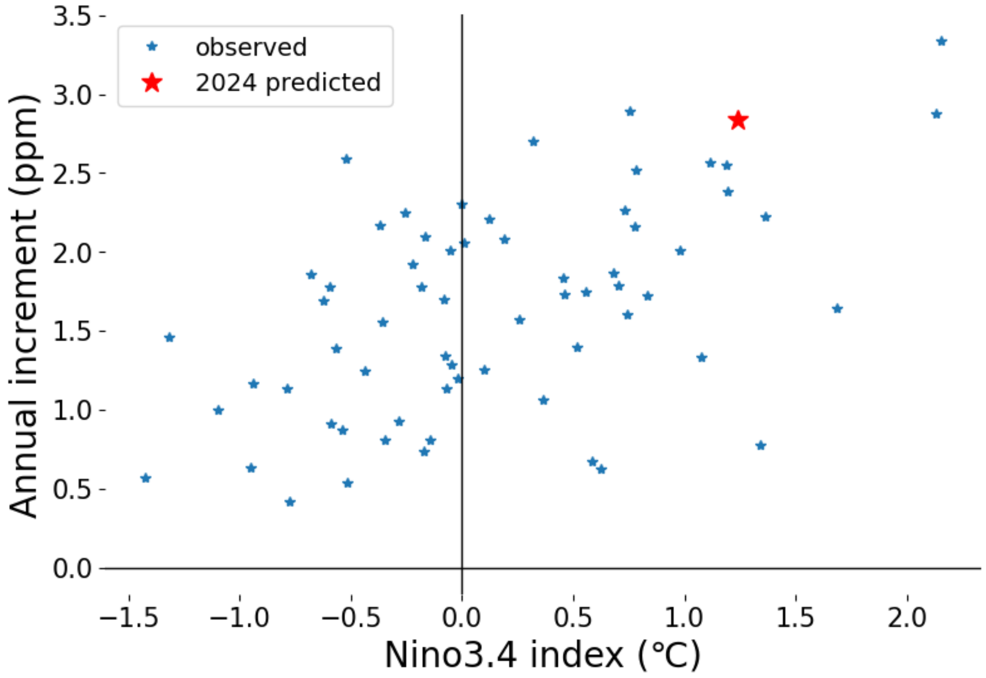

Figure 3. *Annual CO_2 growth rate for years 1960 to 2023 and predicted for 2024 relative to the preceding year, vs. the Niño3.4 index for April of the preceding year to March of the current year. The Niño3.4 index is the sea surface temperature (SST) anomaly in region 5°N to 5°S and 170°W to 120°W in the Pacific Ocean, de-trended to remove the effect of long-term warming.*

This shows that for short periods such as individual years, the observed rate of build-up of CO_2 in the atmosphere does not necessarily reflect the changes in emissions – the effects of climate variability on the short-term rise can dominate. However, in the longer term, the ongoing increase in the annual rate of CO_2 rise is quite evident despite large interannual variability (Figure 4). When the effects of ENSO are removed, the calculated CO_2 rise shows an ongoing increase, with a slower rate after the early 2010s due to the slowing of the rise in global emissions. There was also a temporary slowing of the ENSO-adjusted CO_2 rise in 2020 due to the reduction in global emissions following worldwide reductions in transport and energy production to the COVID-19 pandemic.

Impact of El Niño on the forecast CO_2 rise in 2024

We can estimate the potential contribution of El Niño conditions to the CO_2 rise forecast for 2024 by repeating our forecast calculation without the sea surface temperature change, ie: with "neutral" conditions. This suggests that without an El Niño response in the atmosphere and tropical land ecosystems, the forecast annual mean CO_2 rise from 2023 to 2024 would be 2.34 ppm, a slower rise than the 2.84 ppm forecast when accounting for El Niño (Figure 4).

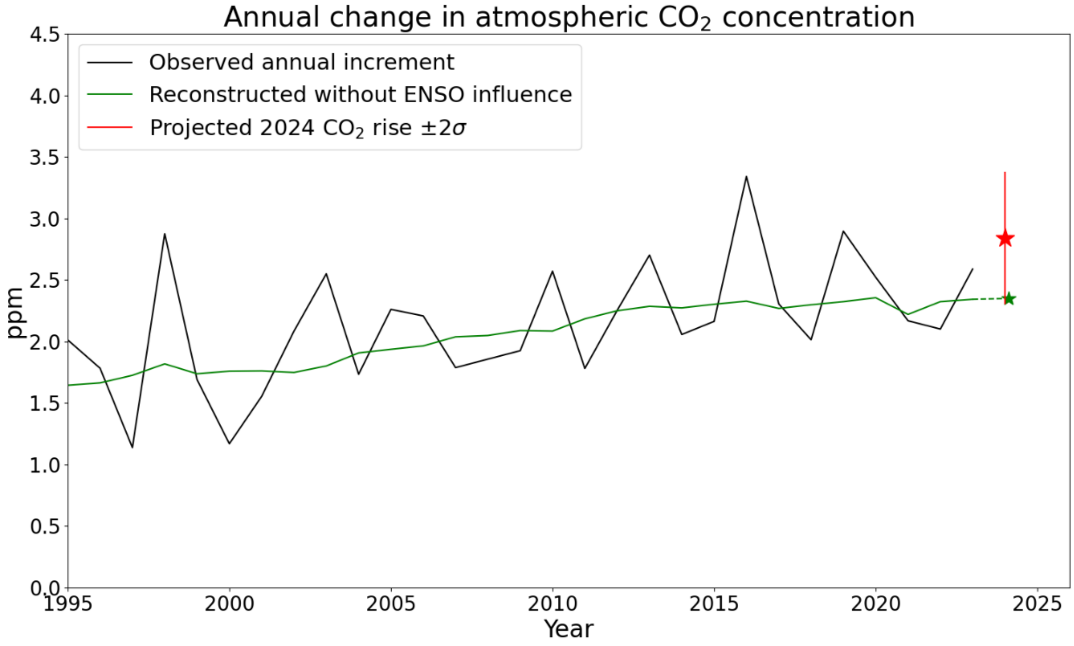

Figure 4: *Annual increments in CO_2 concentration at the Mauna Loa observatory from observations (black) and the 2024 forecast (red star), and the estimated increments without the influence of ENSO (green line and green star). The forecast uncertainty range (red line) is ± 2 standard deviations. Observations are from the Scripps Institution of Oceanography, UC San Diego.*

Comparison with previous annual CO_2 increments

The average annual CO_2 rise has increased consistently over the 6 decades of the Mauna Loa record (Table 1), due to ongoing rise in human-caused emissions. As a result of the influence of an El Niño year causing a relatively large CO_2 increase compared to recent years, the central estimate of the forecast CO_2 rise of 2.84 ± 0.54 ppm for 2023-2024 would be the 4th largest annual increment in the Mauna Loa record of 65 years (Figure 5). Considering the uncertainty range of ± 0.54 ppm, it would be between the 1st and 11th largest annual increments.

Table 1. Decadal average annual CO_2 rises in the Mauna Loa record

Decade	Average CO_2 rise (ppm per year)
1960s	0.86
1970s	1.22
1980s	1.58
1990s	1.55
2000s	1.91
2010s	2.41

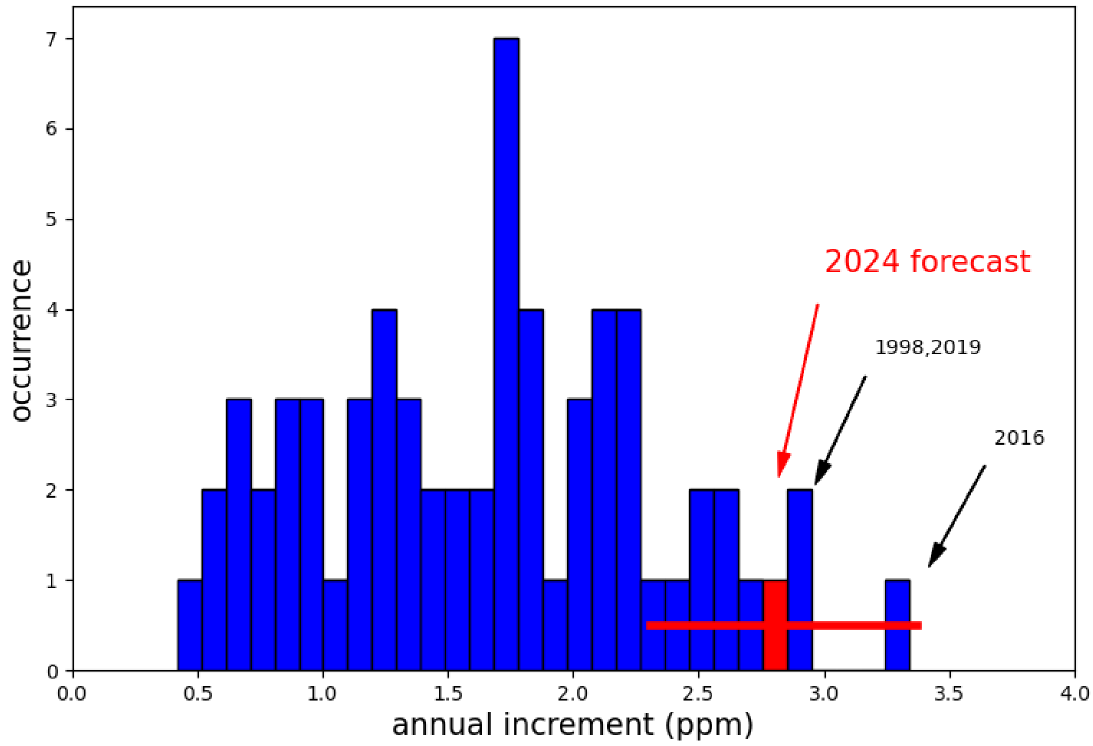

***Figure 5**. The central estimate of the forecast annual CO_2 increment for 2023-2024 in the context of the frequency distribution of the observed annual increment for each year in the Mauna Loa record. The horizontal red bar shows the forecast uncertainty range of ± 0.54 ppm.*

Comparison with CO_2 trajectory consistent with limiting global warming to 1.5°C

The Paris Agreement commits nations to pursuing efforts to limit the rise in global temperatures to 1.5°C above pre-industrial levels. In modelled scenarios that achieve this, the rise in atmospheric CO_2 slows rapidly and ceases completely within the next two decades. The IPCC 6th Assessment Report included 3 scenarios which have at least a 50% likelihood of limiting global warming to 1.5°C with little or no overshoot (Table 2). The C1-IMP-LD scenario features efficient resource use and changing consumption patterns leading to low demand for resources; C1-IMP-REN focusses on renewables; and C1-IMP-SP illustrates shifting global pathways towards sustainable development. Other scenarios could also be followed, but all would require the rise in CO_2 to slow to zero urgently for global warming to be limited to 1.5°C, unless interventions such as solar radiation modification were assumed.

Table 2. Decadal average CO_2 rises in three illustrative scenarios limiting global warming to 1.5° with little or no overshoot (IPCC 2022).

Decade	Average CO_2 rise (ppm per year)		
	C1-IMP-LD	C1-IMP-REN	C1-IMP-SP
2020s	1.33	1.75	1.79
2030s	-0.14	0.13	0.57
2040s	-0.53	-0.46	-0.07
2050s	-0.65	-0.61	-0.41

The IPCC scenarios can provide a benchmark against which the observed and forecast atmospheric CO_2 rise can be compared as part of assessing progress towards the Paris Agreement goal. Figure 6 shows that this year's projected faster rise in CO_2 concentration (red star) is well above all three 1.5°C-compatible scenarios (grey, blue and purple plumes). The faster rise associated with weakened carbon sinks due to El Niño conditions is expected to be temporary. Nevertheless, when this effect is excluded (green star), anthropogenic emissions would still cause the CO_2 rise in 2024 to be well above the rate required to track the "low demand" 1.5°C scenario (grey plume), and at the upper end of the uncertainty range for the other two 1.5°C scenarios (blue and purple plumes).

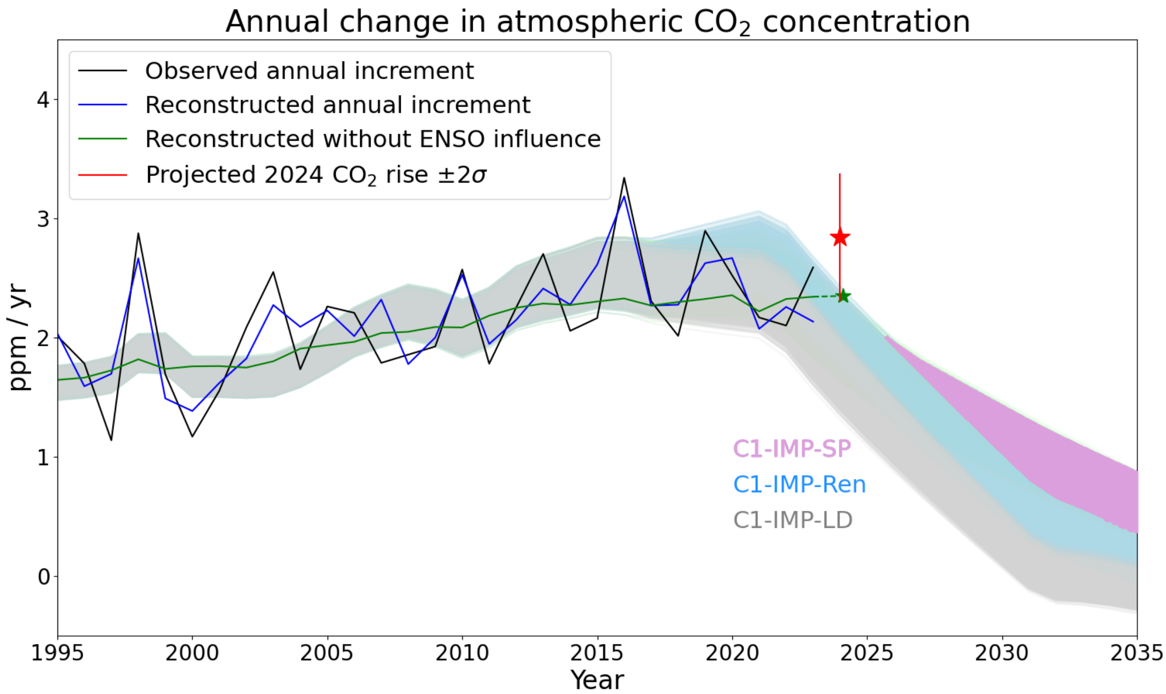

Figure 6. *Comparison of recent and forecast annual CO_2 increments with illustrative scenarios limiting global warming to 1.5°C. Black line: Annual increments in CO_2 concentration at the Mauna Loa observatory from observations. Blue line: Annual increments in CO_2 concentration at the Mauna Loa observatory reconstructed using statistical relationship between concentrations, emissions and ENSO. Red star: the 2024 forecast increment. Green line and green star: Estimated increments without the influence of ENSO. Plumes: simulated CO_2 concentrations in scenarios limiting global warming to 1.5°C with >50% likelihood, focussing on low resource demand (grey plume), renewables (blue plume) and shifting towards sustainable development (purple plume).*

If atmospheric CO_2 concentrations were to follow the "low demand" scenario limiting global warming to 1.5°C, the average annual CO_2 rise over the 2020s would need to be less than half of that forecast here for 2024 (Table 2). This would only be achievable by immediate and substantial cuts in global CO_2 emissions.

The speed with which the CO_2 rise needs to slow for global warming to be limited to 1.5°C can be further put into context by extending the Keeling Curve with projected concentrations from an illustrative 1.5°C-compatible scenario (Figure 7).

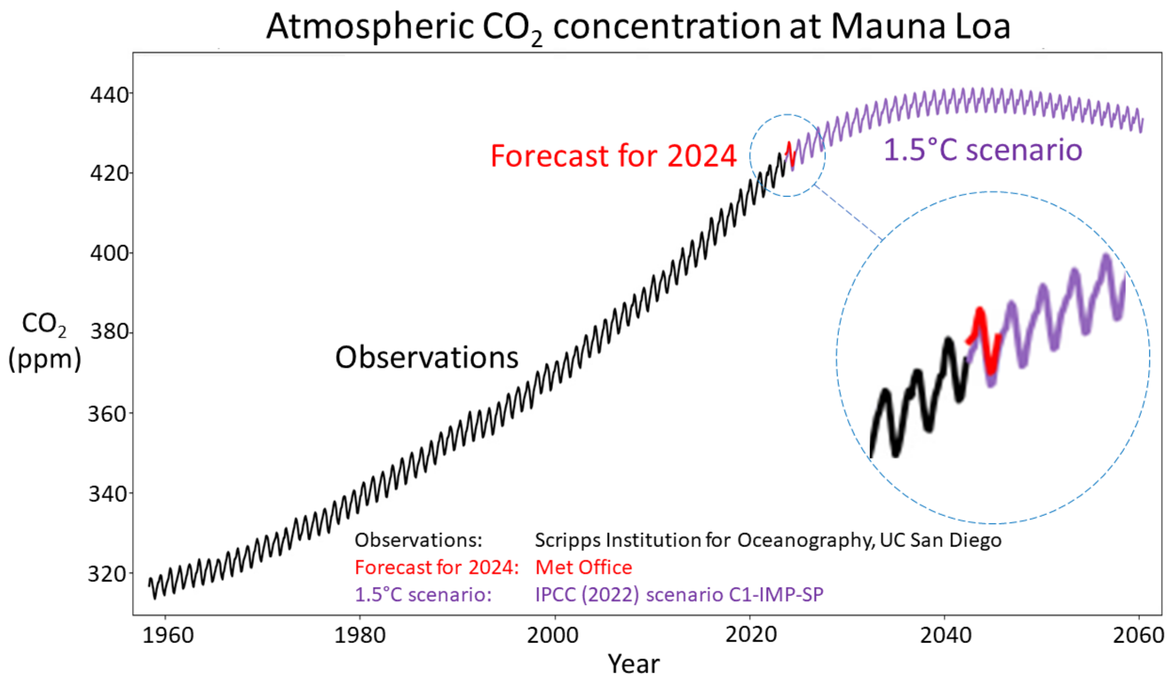

Figure 7. *Monthly CO_2 concentrations from observations up to 2023 (black) and a future projection consistent with limiting global warming to 1.5°C (purple). Also shown is the Met Office forecast for 2024. Observations are the Keeling Curve record at Mauna Loa, from the Scripps Institution for Oceanography, UC San Diego, which began in March 1958. From 2023 onwards, monthly values are calculated from the annual mean concentrations in the C1-IMP-SP scenario, with an illustrative seasonal cycle imposed which continues the amplitude seen in recent years.*

Seasonal cycle of CO_2 concentrations

We also predict the maximum and minimum monthly values in the seasonal cycle of CO_2 concentrations at Mauna Loa (Figure 1, Table 3). Each year, the CO_2 at Mauna Loa increases in the first 5 months, peaks in or around May, then declines for the next 4 months due to the uptake of CO_2 by land ecosystems in the northern hemisphere growing season. Following a minimum, which is usually in September, atmospheric CO_2 then increases again as autumn and winter leaf-fall and decay cause a release of CO_2 back to the atmosphere. In 2024, we predict this seasonal cycle to peak at a monthly mean value of 426.6 ± 0.5 ppm in May (Figure 1, Table 3). From comparison with reconstructions of past CO_2 levels from isotopes of carbon and boron in marine sediments, this will be the highest atmospheric CO_2 concentration for over 2 million years. CO_2 will then return to a minimum monthly value of 420.7 ± 0.5 ppm in September before rising again.

Methods

The technique used to make this forecast was also used to make forecasts ahead of time for 2016, 2017, 2018, 2019, 2020, 2021, 2022 and 2023. In 2020 we also issued an updated forecast once it became clear that the response to the Covid-19 pandemic would cause global CO_2 emissions to be much smaller than expected that year.

Table 3. Forecast monthly average CO_2 concentrations at Mauna Loa in 2024. The 2 standard deviations uncertainty is ± 0.5 ppm

Month	Forecast CO_2 concentration (ppm)
January	423.6
February	423.9
March	424.2
April	425.6
May	426.6
June	426.1
July	424.1
August	422.1
September	420.7
October	420.9
November	422.6
December	424.0

Our usual methodology uses a statistical relationship between the annual CO_2 rise, human-caused emissions and changes in sea surface temperature (SST) in the equatorial Pacific Ocean as a measure of the strength of the dominant pattern of natural climate variability that is known to affect the strength of carbon sinks. We use an average of SSTs from ocean observations in recent months and seasonal forecasts for the coming months. Previous work found that the CO_2 increment between 2 consecutive calendar years correlates most strongly with the SSTs in the 12 months from April to March within those 2 years.

For most years from 2016 to 2023, our forecast calculations used the annual emissions from the previous year as published in the Global Carbon Budget, as normally the ongoing trend in emissions is not large enough to affect the forecast substantially. Our original forecast for 2020 also made this assumption, while our revised 2020 forecast included an adjustment based on projected emissions profiles across the year applied to an atmospheric transport model. Our forecast for 2021 assumed that global emissions had returned to approximately 2019 levels, having already returned to near those levels at the end of 2020. Our forecast for 2022 used the fossil fuel emissions for 2019 and land use emissions from 2020. Our forecast for 2023 and 2024 returned to the usual method of using Global Carbon Budget emissions from the previous year.

In our forecast we assign the same uncertainty to monthly and annual values, but this ignores the role of within-year impacts such as periods of fire activity in areas not typically affected by ENSO, or anomalous wind directions at the measurement site at Mauna Loa. Quantification of these additional sources of uncertainty at monthly levels are a topic of ongoing research and our stated uncertainty on the monthly averages will therefore be an underestimate.

Verification of previous CO_2 forecasts

The observed annual mean CO_2 concentration in 2023 at Mauna Loa was 420.8 ppm, higher than forecast and outside the uncertainty range of 2 standard deviations. The monthly forecast concentrations verified well against observations until March, but from April onwards the observed concentrations were higher than forecast (Figure 8, Table 4). It is expected that was because the Met Office forecast used sea surface temperatures from April 2022 to March 2023 which was dominated by La Niña conditions, so the forecast was for a smaller CO_2 rise. However, in 2023 El Niño conditions emerged earlier than usually occurs, strengthened rapidly and remained for the rest of the year. It seems likely, therefore, that the impacts of this on weakening natural carbon sinks became well established during calendar year of 2023, outweighing or cutting short the strengthening of carbon sinks that was expected to have occurred as a result of La Niña conditions in 2022 and early 2023. However, further research is needed to establish the extent of the impact of El Niño in 2023.

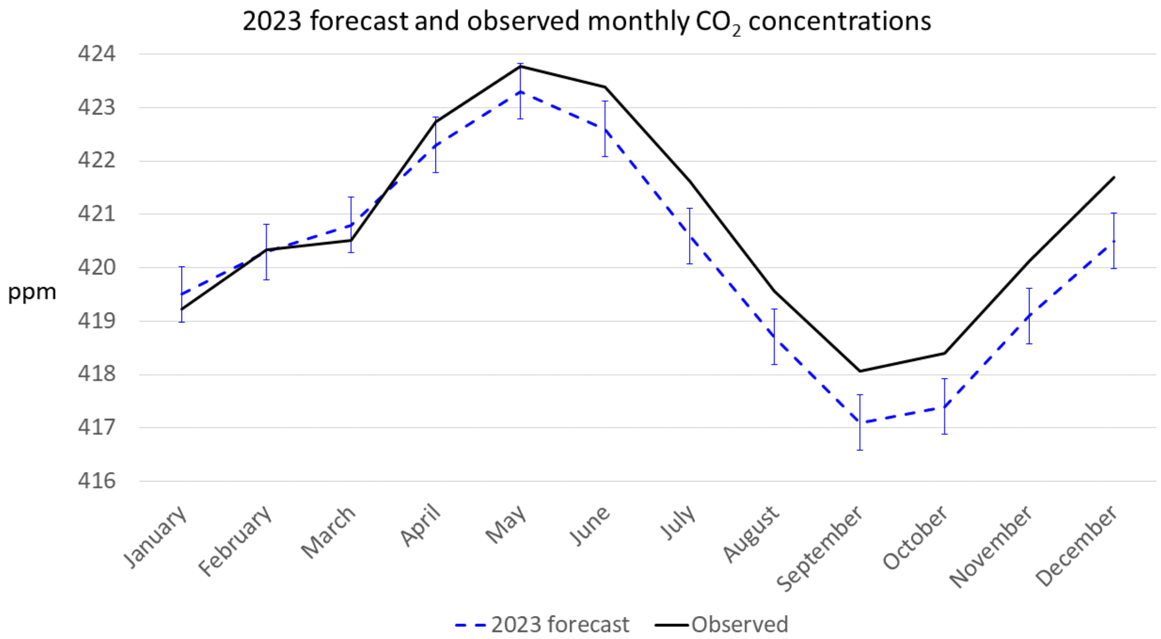

Figure 8. *Comparison of Met Office forecasts of monthly CO_2 concentrations in 2023 at Mauna Loa (dashed blue line) with measurements for 2023 (solid black line) from the Scripps Institution for Oceanography UC San Diego. The vertical blue lines show the forecast uncertainty range (2 standard deviations).*

2023 was the first year since we began our forecasts in 2016 for which the observations were outside the forecast uncertainty range of 2 standard deviations (Table 5). Moreover, it was the first year in which our method for including the effect of ENSO variability brought the central value of the CO_2 rise forecast further from the observations than when considering anthropogenic emissions alone (Figure 9). In all years up to 2022, our method for including the ENSO impact had led to a more accurate CO_2 forecast.

Table 4. Forecast and observed monthly average CO_2 concentrations at Mauna Loa over 2023. The uncertainty in the forecast values was ±0.5 ppm. Observed monthly averages are those published by the Scripps Institution for Oceanography at UC San Diego.

Month	Forecast (ppm)	Observations (ppm)
January	419.5	419.2
February	420.3	420.3
March	420.8	420.5
April	422.3	422.7
May	423.3	423.8
June	422.6	423.4
July	420.6	421.6
August	418.7	419.6
September	417.1	418.1
October	417.4	418.4
November	419.1	420.1
December	420.5	421.7

Table 5. Summary of forecast and observed annual CO_2 concentrations and rises for 2016 to 2023. Note that observations are not available from 28th November 2022 onwards due to the eruption of the Mauna Loa volcano cutting off power supplies to the observatory, so for 2022 the comparison of forecast and observed mean concentration is given for January-November, and the forecast and observed increases are calculated relative to the January-November mean for 2021. For 2020, both the original forecast and the updated forecast accounting for the Covid-related emissions reductions are shown.

Year	Forecast CO_2 increase from previous year (ppm)	Observed CO_2 increase from previous year (ppm)	Forecast annual mean CO_2 concentration (ppm)	Observed annual mean CO_2 concentration (ppm)
2023	1.97 ± 0.52	2.57	420.2 ± 0.52	420.8
2022	2.14 ± 0.52	2.11	418.3 ± 0.5	418.2
2021	2.29 ± 0.55	2.10	416.3 ± 0.6	416.1
2020 (updated	2.48 ± 0.57	2.52	414.0 ± 0.6	414.0
2020 (original)	2.74 ± 0.57	2.52	414.2 ± 0.6	414.0
2019	2.74 ± 0.58	2.90	411.3 ± 0.6	411.5
2018	2.29 ± 0.59	2.00	408.9 ± 0.6	408.6
2017	2.46 ± 0.61	2.31	406.8 ± 0.6	406.6
2016	3.15 ± 0.53	3.39	404.5 ± 0.6	404.3

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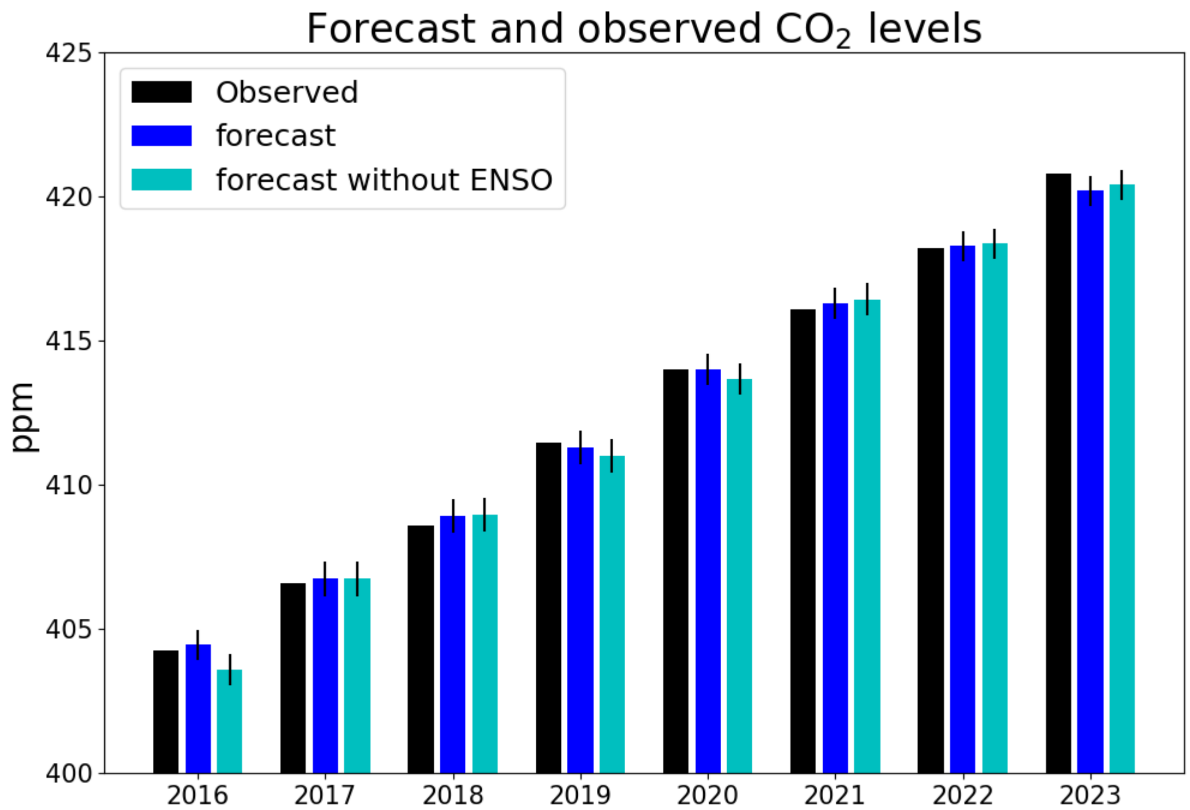

Figure 9. *Observed (black) and forecast (dark blue) annual average CO_2 concentrations for 2016 to 2022, and re-forecast values based on emissions alone, without the effects of ENSO (light blue). Thin black lines show the forecast uncertainty range (2 standard deviations).*

Note: definitions of annual CO_2 rise, increment and growth rate

We define the annual CO_2 rise or annual increment for a particular year as the difference in annual average concentration for that calendar year and that of the previous calendar year. This is different to the definition of annual 'growth rate' as published by NOAA which is the average change across an individual calendar year.

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