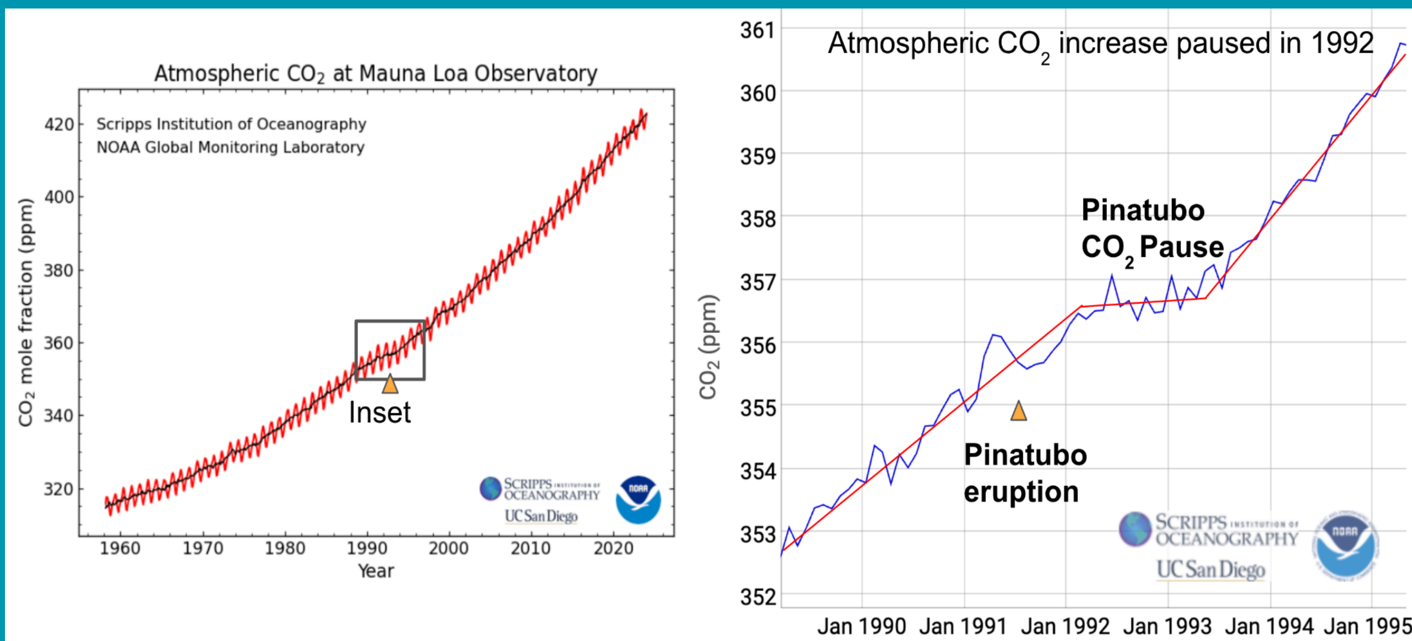
The Pinatubo CO2 Pause —
Can we replicate nature's 1992 net-zero event?



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CLIMATE RESTORATION

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The Pinatubo Pause and Natural Ocean Iron Fertilization

New Analysis of CO2 Data Shows 20 Gt of CO2 Removed Permanently from the Atmosphere in the Year Following the Eruption

The natural net-zero emissions event in 1992 challenges us to repeat it intentionally by 2030.

Author email: pfieko@gmail.com Updated 7 March 2025

Historical CO_2 data from NOAA ("Keeling curve") show a 20 Gt removal of CO2 in the 18 months following the June 1991 Mt. Pinatubo eruption. This corresponds roughly to the amount of CO2 reported emitted from fossil fuel consumption in 1992, thus resulting in the observed "net-zero" emissions that year. CO2 level increase data in the following decades indicates that the removal was essentially permanent (after averaging out El Nino/La Nina cycles over 10-year baselines that exclude the eruption). Consideration of seven hypothetical explanations for the "Pinatubo CO2 pause", show that only a new nitrogen fixation model for ocean iron fertilization (N-OIF) can explain the CO2 removal magnitude, speed, and durability.

The N-OIF model posits that large volume extended CO2 removal can occur when three conditions are met: A) sufficient iron concentration to support nitrogen-fixing cyano-bacteria B) for sufficient time for the bacteria to form a bloom, C) over or near a down-welling eddy. The needed iron concentration is estimated to be roughly 20 times that needed for phytoplankton growth, and it must be maintained for several months. No other eruptions of similar magnitude since the Mauna Loa CO2 record started in 1958 show similar CO2 removal rates and permanence, consistent with the fact that the ash did not occur near a downwelling eddy. Of nine eruptions since 500 that cooled the planet, only three removed measurable amounts of CO2, and those deposited their ash over downwelling eddies.

Significantly, extending this model to multiple tropical downwelling eddies by 2030 could theoretically result in restoring historically safe CO2 levels for humanity and holocene ecosystems by 2050. This strategic application of a demonstrated natural process appears to be the first CO2 removal pathway capable of doing so.

Key Points

- Sarmiento (1993) reported a 1.5 ppm CO2 removal anomaly following the 1991 Pinatubo eruption. The anomaly magnitude was reduced 0.8 ppm by an El Nino event starting before the eruption.

- Analysis of NOAA CO2 data including the preceding and following decades to average out El Nino effects indicates a multi-decade 2.3 ppm (20 Gt) CO2 removal anomaly in 1992 and early 1993 (figure 2).

- Quantitative analysis of seven proposed explanations for the CO2 pause show that only one candidate is physically plausible. That is ocean fertilization in a downwelling eddy, in which nitrates are replenished by nitrogen fixing bacteria growth (nitrogen fixing OIF or N-OIF) enabled by high iron levels over several months. Ocean cooling effects and land photosynthesis pathways are too small by several orders of magnitude and would be limited to 1-2 years durability.

- Most of the 20 Gt decrease, compared to the expected atmospheric CO2 trend, likely took place within the ash fall region (an arc 600 kilometers long) west of the eruption (Haeckel et al. 2001) —a region that is roughly 0.1% of the global ocean area. The region was coincidently centered on a recurring 350 km downwelling ocean eddy (figure 6).

- The required rate of CO2 removal is consistent with rates reported in other ocean regions, 14 grams of carbon removal per square meter per day (14 g C/m^2/day).[1] While high, this rate lies well within the range observed in high "primary productivity" areas, which reach 20 g C/m^2/day. (Danieri et al. 2000).

- The Pinatubo-induced carbon removal—20 Gt CO2 per year—is five times the maximum CDR potential for OIF proposed by an influential study (GESAMP 2019). The GESAMP study suggests that global OIF could remove only 1 Gt of carbon (3.7 Gt of CO2) per year as the effectiveness of iron fertilization would be limited by available nitrogen (nitrates). Specifically, CDR from OIF in the South China Sea would be low because of existing low nitrogen levels. The observed Pinatubo data contradicts this conclusion, favoring instead a view that high iron and phosphorus availability from volcanic ash enabled production of nitrates by nitrogen-fixing cyanobacteria (Bonnet et al., 2023, Price 1991, Karl et al 2002, Bergman et al 2012), and that a downwelling eddy may have moved much of the carbon fixed by photosynthesis to suitable depths before it could be eaten and metabolized by other organisms.

- Antarctic ice core data provides evidence for a maximum historical removal rate (averaging multi-decade periods) of 4.5 Gt CO2 / year.[2] The period 1580 to 1610 shows removal rates of 0.37 ppm / year, or 3.3 Gt CO2 / year.[3]

[1] Haeckel estimates that roughly 1 million km^2 received significant volcanic ash, roughly ⅓ of the South China Sea. 20 Gt CO2 is 5.3 Gt carbon. Divide by 365 days and 10^6 km^2 corresponds to 14 g C/m^2/day.
[2] NOAA ice core data from 12,000 to 800,000 years ago shows that the maximum annual CO2 loss averaged over an 11 year period to be 0.5 ppm / year, 14,541 years ago. While this is a quarter of the magnitude recorded in 1992, the ice core data averages from 10 to 40 years, so that single year extremes, such as 1992, are averaged out.
[3] Ahn et al, 2012 Atmospheric CO2 over the last 1000 years: A high-resolution record from the West Antarctic Ice Sheet (WAIS) Divide ice core

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Summary

Climate restoration—reducing CO2 to historically safe levels below 300 ppm by 2050—requires net removal of 60 Gt CO2 per year from 2030 to 2050—nearly twice current CO2 emissions. The observed removal of 20 Gt of atmospheric CO2 following the 1991 Mt. Pinatubo eruption supports the feasibility of restoring the climate. Evidence suggests that the mechanism for CO2 removal following the eruption was primarily ocean fertilization with induced nitrogen fixation in a downwelling mesoscale eddy.[4] If true, this process might be optimized and replicated in multiple downwelling eddies to achieve global climate restoration.

Intentional climate restoration is controversial because it challenges the accepted 1992 UNFCCC climate goal of preventing human-caused interference to the climate system.[5] The 1992 GHG stabilization goal would have maintained a safe Holocene climate if economic uses of fossil fuels had been terminated at that time, but they weren’t. CO2 levels are now 40% higher than agriculture and civilization have ever survived long-term and higher than anytime since pre-humans evolved 14 million years ago. Levels are increasing by 0.6% annually.

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[4] Mesoscale eddy effects on sea-air CO2 fluxes in the northern Philippine Sea

[5] The UNFCCC says, “*The ultimate objective of all three agreements under the UNFCCC is to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system, in a time frame which allows ecosystems to adapt naturally and enables sustainable development.*” The term ‘dangerous’ is relative to maintaining the status quo, which was Holocene in 1992, but Pliocene now that GHG levels are above 400 ppm.

The subjective moral choice to update our common climate goal to “Restore and stabilize historically safe GHG levels” is beyond the scope of this technical paper. However, in support of that ethical and cultural choice, this article provides important evidence that climate restoration is possible by 2050, a timeframe required to preserve many existing species, ecosystems and cultures. An associated paper indicates that such restoration could be accomplished at a cost below $1 billion per year through 2050.[6]

The aftermath of the 1991 eruption of Mount Pinatubo demonstrated that this scale of carbon-dioxide removal (CDR) restoration may be feasible through intentional reproduction (biomimicry of natural processes). CO2 measurements from the NOAA observatory at Mauna Loa show that after the eruption, atmospheric CO2 levels continued rising at previous rates but were lower by 2.3 ppm (equivalent to 20 Gt CO2) than would be expected. This assumes that global CO2 emissions maintained their steady increase of the previous decade, and El Nino / La Nina impacts were historically consistent.

This 2.3 ppm reduction appears permanent in the three decades following, and is separate from the global cooling of roughly 0.4 C for almost two years that occurred due to reflective sulfate aerosols injected into the stratosphere. The aerosol-related cooling lasted about 18 months, while the CO2 removal lasted about 12 months and appears to be essentially permanent.

The only hypothesis proposed that explains more than 2.6% of the long-term reduction in CO2 levels is that iron in the volcanic dust led to healthy phytoplankton and cyanobacteria blooms, in which cyanobacteria providing needed nitrogen and volcanic ash providing phosphorus in the iron-rich water. Such “iron fertilization” has been shown to be the major mechanism at work in rapid CO2 decreases leading to ice ages. Other hypotheses—relating to land-based photosynthesis, increased solubility of CO2 in cooler oceans, and emission reductions following the collapse of the USSR—do not fit the magnitude or duration of the observed CO2 removal.

The NASEM 2022 report on ocean CDR concluded that theoretically ocean iron fertilization (OIF) could remove at most 3.7 Gt of CO2 a year. However, the CO2 concentration following the eruption indicates the theory requires adjustment, such as including the known phenomenon of nitrogen fixation when iron levels are sufficiently high.

Mt. Pinatubo Eruption effects

Following the eruption of Mt. Pinatubo in the Philippines in June of 1991, the globe cooled about half a degree Celsius. This phenomenon lasted 1-2 years and is well known. The cooling is generally attributed to an increase of sulfate aerosols in the stratosphere, which reflected about 0.5% more sunlight into space.

Less well known is that, separate from the cooling effect of volcanic aerosols, CO2 levels also fell about 2.3 ppm, representing 20 Gt removed from the atmosphere. Judging by CO2-level trends during the 10 years prior and 20 years after, this removal appears to be permanent.

[6] Cost-Effectiveness of Carbon-Dioxide Removal Methods

Several potential sinks for the 20 Gt of removed CO2 have been proposed. Only ocean iron fertilization (OIF) explains the permanence of the removal. OIF, the topic of the “iron hypothesis”, is thought to have produced most of the roughly thousand Gt CO2 removal before ice ages observed in the historical record.

OIF tests over the last 20 years have shown local reductions in CO2 levels of 50 to 90 ppm at the sea surface. We estimate that the sea surface CO2 level reduction during the Pinatubo pause would have been about the same.[7]

[7] To compute surface-level CO2 during the year of the Pinatubo pause: Assume 2.3 ppm CO2 removed over 1 year, over a 350 km diameter eddy, with wind speed 35 km / hr and vertical mixing of 1 km is about 50 ppm. The airmass (350 km diameter x 35 km/hr wind x 8760 hr / year area) is 107 million km2. This is 20% of the Earth’s area each year, times 5 percent of the atmosphere is below 1 km elevation. Conclusion: To remove 2.3 ppm from the total atmosphere would require removing 50 ppm over the ash-fall site (the 350 km diameter downwelling eddy).

Seven hypotheses to explain the 1992 “Pinatubo Pause”

	CO2 removal mechanism	Perm anent	CO2 Gt reduced or removed	Notes
1	OIF (w/ N, P sources)	yes	20 Gt	N from cyanobacteria, P from ash (Quimbo 2020)
2	Cooled ocean dissolves more CO2	no	0.002 Gt 1-2 years	Assumes 0.3C average ocean temperature decrease in 200 m mixed layer
3	Increased land plant growth: ash fertilization	no	0 Gt	Krakauer et al 2003
4	Increased land plant growth: more diffuse light	no	0 Gt	1% less sunlight leads to less growth on average, not more
5	Reduced emissions after fall of Soviet Union	yes	0.7 Gt	Global emissions fell 2.6% 1991-1992 (EPA, Statista)
6	Alkaline ash	yes	0.01 Gt	15 Gt ash X 5% alkaline x 1% dust x .62 t CO2 per ton of olivine
7	Dust dispersed around the world led to global OIF	yes	0 Gt	Iron concentration would be 0.03% of the requirement for cyanobacteria.

1. **The Iron hypothesis** (OIF)[8] is the only known hypothesis that fits the observed multi-decadal data. Of the 15 billion tons (5 cubic km)[9] of volcanic dust released, one millionth could have been usable iron compounds, deposited into the South China Sea, west of the volcano, to produce that impact. Dacite, the primary mineral in the eruption, contains 2% to 4% iron oxide. In addition 0.1% could have been phosphorus from apatite. The pre-eruption availability of nitrogen and phosphorus in that ocean area is thought to be insufficient for the amount of carbon sequestration observed. However sources of those minerals, such as nitrogen fixing bacteria and phosphorus in the volcanic ash [10] (Quimbo

[8] 30 years of the iron hypothesis of ice ages
[9] The Cataclysmic 1991 Eruption of Mount Pinatubo, Philippines, Fact Sheet 113-97
[10] Quimbo 2020 thesis. The impact of the 1991 Plinian eruption of the Mt. Pinatubo, Philippines on soil development, phytolith accumulation, phosphorus status, and crop productivity

2020) could have provided the needed macronutrients. "Vertically migrating phytoplankton fuel high oceanic primary production" offers another pathway to provide N and P. The photosynthesis (primary productivity) rate required is within ranges observed in nutrient rich areas of the Pacific Ocean. There were no satellites available to observe the bloom at the time. The SeaWiFS satellite currently used to measure chlorophyll and blooms was launched in 1997, after the eruption.

2. **Cooling, from reduced solar radiation that cooled the ocean by as much as 0.5C, allowed the ocean surface to absorb more CO2** because CO2 dissolves more in cooler water. **Unlikely because the removal was multi-decade but the cooling lasted only 1-2 years and the 20 Gt removal is 300 times more than could occur even if the cooling extended to 200 m.** The CO2 removed would return to the atmosphere the following year when ocean temperatures returned to normal. Further, the amount of CO2 removed would be about 0.006 ppm, [11] 0.3% of the 2.3 ppm removal observed.

   Finally, the 1980 El Chichon eruption, with practically no ashfall in the ocean, produced cooling levels similar to Pinatubo but no measured CO2 removal. This indicates that cooling from a volcano does not cause CO2 removal. The Agung (Bali) eruption in 1963, surrounded by ocean, produced similar cooling and was followed by reduced CO2 for a year, but the CO2 level then rose back to the previous trendline. See Appendix B.

3. **Increased land plant growth due to fertilization from volcanic dust**. **Unlikely because the removal was semi-permanent** and a majority of plant growth is annual. This is most unlikely because the total plant and soil carbon on the island of Luzon would have had to increase 20 fold to absorb the 20 Gt CO2 sequestered. Mature tropical forests hold roughly 250 tons CO2 per hectare, above and below ground. This quantity of CO2 corresponds to 67 tons of carbon. Pinatubo is on the island of Luzon, which covers 10 million hectares, 87% of which has forest cover. So existing carbon sequestration would have been 67 tons / ha x 9 million hectares, or roughly 0.6 Gt of carbon. If the carbon content in Luzon forests increased 50% in 1992, that would constitute just 5.6% of the 20 Gt CO2 (5.3 Gt C) removed. A 50% increase in one year would have been

[11] The maximum additional CO2 dissolved in the ocean with 0.4 °C surface cooling can be estimated by initially assuming that the whole planet is covered by ocean. At 20°C, the average sea surface temperature, the solubility of CO2 in water decreases by 0.08 g CO2 / kg water per degree. This is 8×10^{-5}/ °C. Li 1971 shows that seawater has essentially the same solubility function as water. The average cooling over 1992 was about 0.3C. The ocean mixed layer is 200m in water above 10 °C. Water pressure increases by one atmosphere for each 10 m depth, so 200m has 20 times the mass of the atmosphere above it. It was cooled by less than 0.2 °C on average. This would result in a fractional absorption of roughly 3.2×10^{-4} of atmospheric CO2. At 360 ppm in 1992 that is (8×10^{-5} solubility/°C x 0.2 °C x 20 (mass of mixed layer / mass of atmosphere) x 360 ppm x 0.7 ocean/Earth area) or **0.08 ppm or 0.7 Gt CO2**. During ice ages, with 5 °C cooling, the cooling of the ocean would account for roughly **0.08 ppm x (**6 °C cooling / 0.2) =2.4 ppm or 19 Gt CO2 out of roughly 1000 Gt.

large enough to be reported, and no such reports have been found. Krakauer et al 2003 confirms this.

Increased plant growth outside the island of Luzon would not amount to much. Only trace ash fall was reported in Vietnam, the closest land downwind, 1400 km away (USGS Paladio 1999). See figure 10. With the iron oxide content of the ash being 2% to 4%, the amount of iron added to oceans outside the South China Sea would be insufficient to induce significant phytoplankton or cyanobacteria growth.

A typhoon crossed the region at the time of the eruption, and weakened to light to moderate showers the following day. Its heavy rains probably reduced the widespread distribution of ash (Global Volcanism Project) .

4. **Increased diffuse light caused Increased growth of land plants**. **This is unlikely because most plants grow less, not more, with decreased sunlight and understory plants are mostly not woody.** Since too much sun can adversely affect plant growth some theorize that the roughly 1% reduction in direct sunlight reaching Earth's surface, and about 0.5% more scattered light, significantly increased photosynthesis on land. This presumes that an enormous mass of plants are sun-stressed. Even if that were the case, most additional sequestered carbon would return to the air in the following year as leaves and seeds decay. However, the observed CO2 removal was permanent.
5. **Reduced emissions related to a reduction in GDP growth and the collapse of the Soviet Union in Dec, 1991**. **Unlikely because global emissions were essentially unchanged 1991 to 1993.** A 95% global emission reduction during 1992 would be required to explain the pause.

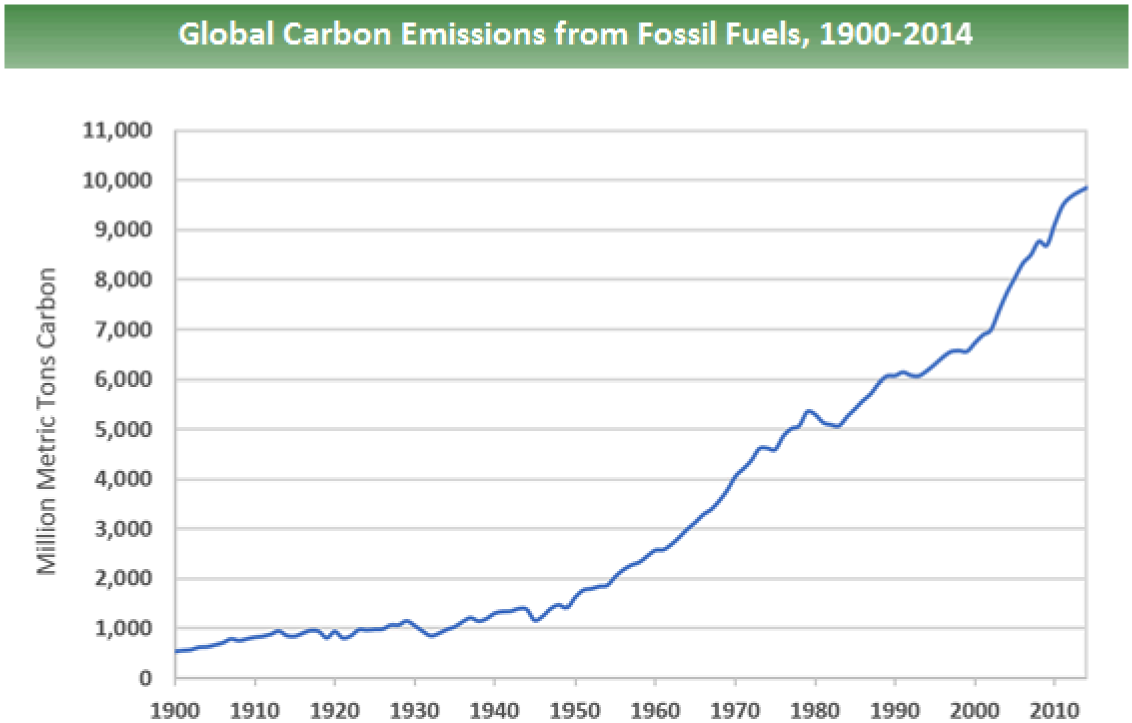


Figure 1. Fossil fuel emissions stayed essentially constant in 1991-92 (shown in Gt carbon per year; multiply by 3.7 for Gt CO2) From US EPA

6. **Alkaline volcanic ash absorbed acidic CO2 in the ocean as the now-trendy ocean alkalinity enhancement (OAE). Unlikely because there was not enough rock distributed.** The eruption involved 5 km^3 of rock, weighing 10-15 Gt. Most of the rock was acidic dacite and neutral andesite, and was not finely ground. Alkaline rocks (an unknown percentage of the eruption) such as olivine remove 0.62 tons of CO2 per ton of rock, typically over a period of years. Thus if 5% of the rock was alkaline and 1% of that was fine dust, then alkalinity would account for less than 0.1% of the observed CO2 reduction.

7. **Iron-rich dust spread around the world, especially the Southern Ocean,** similar to the sulfates that caused 0.5C cooling. **Highly unlikely because the amount of ejecta**

was too small by a factor of 3000 to achieve that result, and would not produce iron concentrations high enough to support phytoplankton, much less cyanobacteria.[12]

Nitrogen fixing OIF hypothesis

A high concentration of iron, available for over three months, could allow the growth of sufficient nitrogen-fixing phytoplankton, likely Trichodesmium (Bergman et al 2012), to produce the nitrates required for removal of 10 to 20 Gt of CO2. Trichodesmium growth is optimal at temperatures 20-34 C, commonly between 20˚N and 20˚S. It requires considerably higher iron concentrations than ordinary phytoplankton, initially roughly 20 times more (Kustka 2003). The growth rate of Trichodesmium is roughly ten times slower than other phytoplankton. It is said that a Trichodesmium bloom typically requires three months to develop. The Mauna Loa CO2 data shows that a CO2 level plateau started six months after the eruption, consistent with the slow Tricho. growth rate.

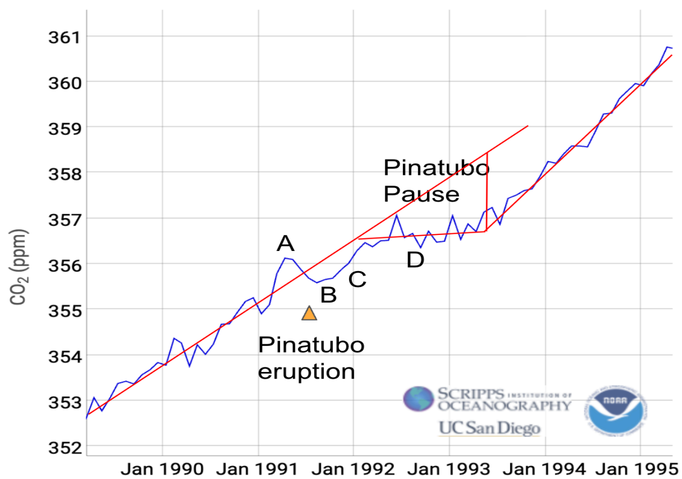


Figure 2. Mauna Loa CO2 levels before and after the Mt. Pinatubo eruption. Note that roughly 55 days are required for CO2 changes near Mt. Pinatubo to be blown by trade winds around the world to the Mauna Loa CO2 monitoring laboratory. Proposed timeline:

A: Pre-eruption CO2 burst;

B: Post-eruption CO2 removal, limited by N;

[12] Standard OIF requires about 1 kg iron sulfate per km^2 (1 mg / m^2) of ocean per application (lasting ~5 weeks), based on 2012 tests. Supporting nitrogen fixing organisms requires 20 times that much (0.02 ton / km^2). Initially we assume that the dust becomes evenly distributed around Earth and is deposited over 12 months, similar to the sulfates that cooled the planet. Earth has an area of 5 x 10^8 km^2. The total amount of iron sulfate required to sustain OIF in regions beyond 1400 km downwind from the eruption would be 1 x 10^7 tons, averaged over 10 times per year. If we assume 3% iron in the ash, that requires emission of 3 x 10^9 tons of suitably fine dust. USGS data from Mt. St. Helens (1980) shows that beyond 600 km most ash is smaller than 4 microns. USGS reports that Vietnam reported 'trace' amounts of dust 1400 km from Pinatubo. The lack of reports further than Vietnam suggests that no ash was observed. The fraction of rock emitted as ash in that size range appears to be below 10^{-4} based on the USGS report. Total ejecta was estimated to be 10^{10} tons (USGS), of which perhaps 10^6 tons would have been smaller than 4 microns. This is 0.03% of the required 3 x 10^9 tons. For comparison, USGS estimates 10^7 tons of SO_2 were injected into the stratosphere. This turned into heavier H_2SO_4. This is 3 ½ orders of magnitude too small. More careful calculations are needed but are unlikely to change this result significantly.

C: Slow growth of N fixing phytoplankton;
D: Continued CO2 removal fueled by N fixing phytoplankton

The reduction of CO2 by 0.4 ppm in period B corresponds to a removal of 3.2 Gt CO2. Using the Redfield C:N ratio of 106:16, this suggests that 0.5 Gt of nitrogen were consumed during the 3-4 month period following the eruption.

Analysis of CO2 levels (Keeling Curve), 1980 to 2014

The record of CO2 levels since 1958 was originated by Charles Keeling and is known by his name. CO2 data obtained at Mauna Loa clearly show a hiatus in the increase of atmospheric CO2 between 1991 and 1993. The average CO2 level increase was 1.7 ppm per year in 1995. In the two years between April of 1991 and April 1993 CO2 increased by 0.7 ppm (0.35 ppm per year) while a 3 ppm increase was expected from trends, a loss of 2.3 ppm, corresponding to 20 Gt as a fraction of Earth's atmosphere. Eighteen months after the eruption, CO2 levels resumed their increase at 1.7 ppm per year, but from a lower baseline, 2.3 ppm below the trend before the eruption. There is no evidence of the removed CO2 reappearing in the 30 years following the eruption.

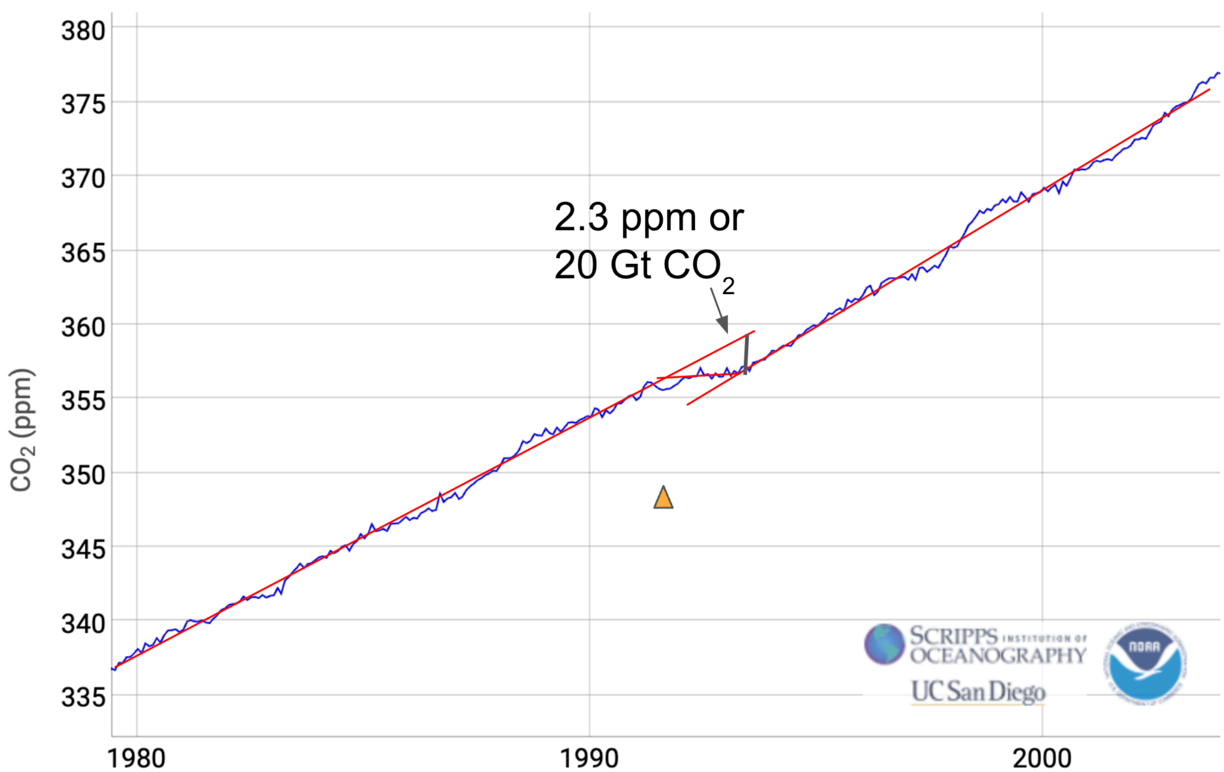


Figure 3. Monthly CO2 averages from Mauna Loa, with 10-year trendlines, pre-eruption and post eruption. NOAA monthly trend data for the period. The strong 1998 El Nino and 1999 La Nina period is visible, shown in fig. 5 below. The offset in the 10-year trends is about 2.3 ppm, corresponding to 20 Gt CO2 permanently removed. The trendline slope increased 15% from 1.53 ppm / year in 1981-1991 to 1.77 ppm / year from 1993 to 2004. Global emissions increased a similar 15% from 25.6 to 29.4 Gt / year during that same period (Carbonbrief).

When CO2 levels are computed by annual averages, the change in trajectory again shows the dramatic halt in CO2 growth, 1992-93. It also shows the 2.3 ppm decrease in the trendline that continues long after the Mt Pinatubo eruption (Figure 2).

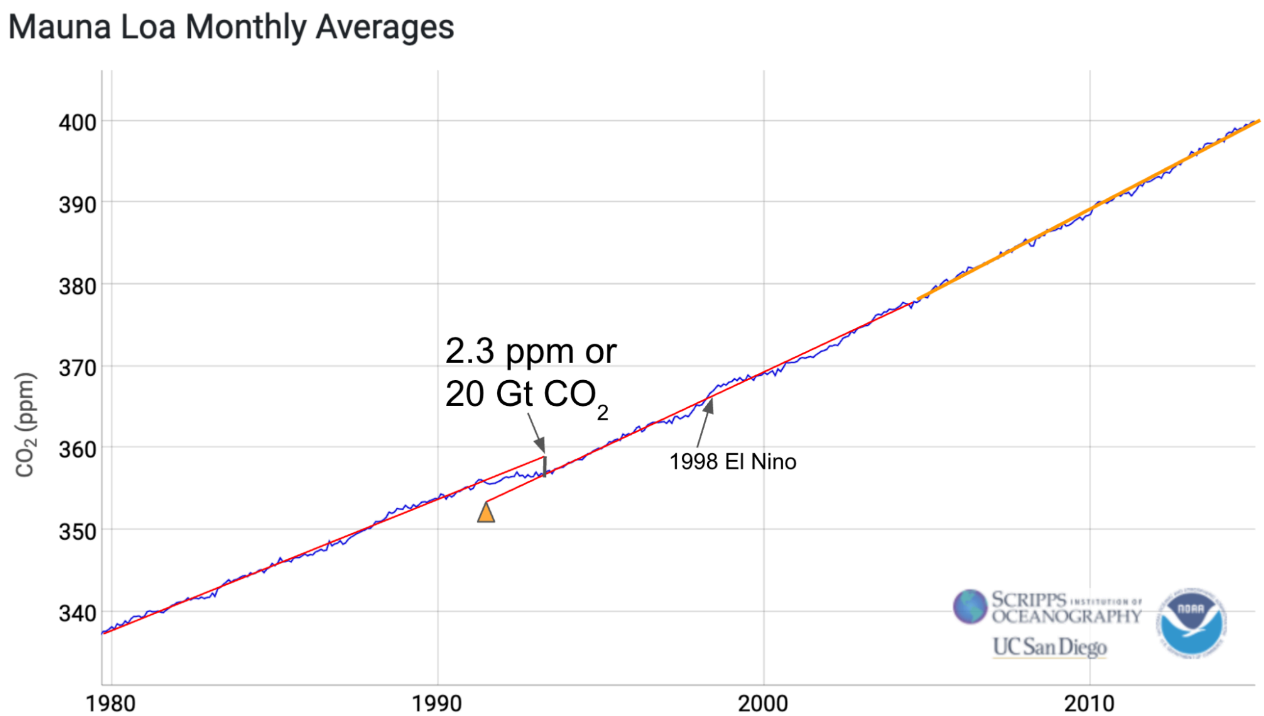


Figure 4. NOAA Monthly CO2 levels (Mauna Loa), monthly averages with 10-year baselines to average out El Nino events. It shows a 2.3 ppm offset between 10 year pre-eruption and post-eruption baselines from 1993. Current OIF theory only allows 1-4 Gt annual removal.

Decade starting	Annual CO2 increase (ppm / year)	Global CO2 Emissions (Gt / year)	CO2 annual Gt emission / ppm incr.	CO2 level	CO2 incr over 285 ppm
1980	1.64	25.5	15.6	338	53 ppm
1996	1.88	30.9	16.4	362	77 ppm

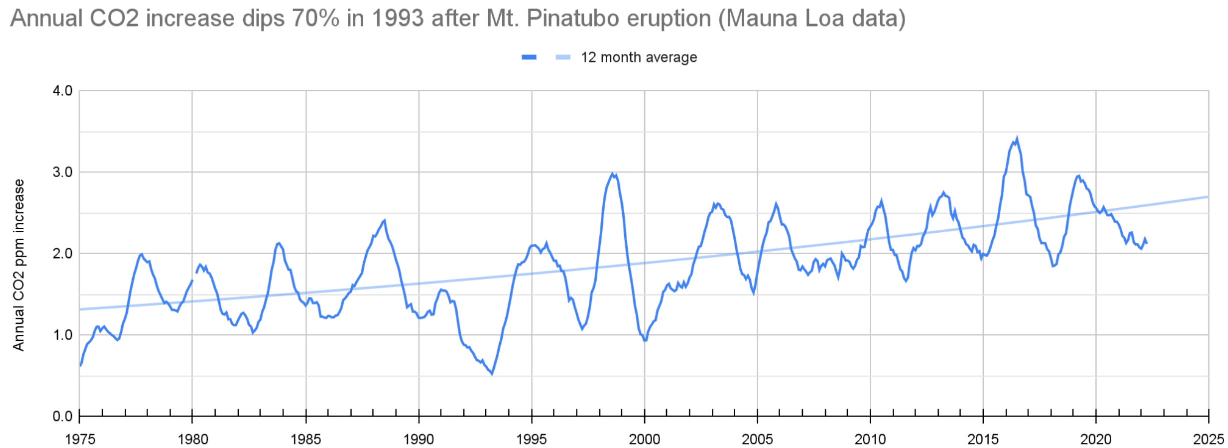
2006	2.04	37.0	18.1	381	96 ppm
2024	2.8	41	14.6	426	141
Incr 2006 / 1980	24%	45%			55%

Table 1. The ten year CO_2 baseline slope increased from 1980 to 2016 as emissions increased (shown in figure 4). Note that the CO_2 emissions corresponding to 1 ppm have increased 16% since 1980. Emissions increased 24% during that period. This indicates a larger CO_2 partial pressure difference between the atmosphere and ocean. The increased partial pressure difference from increased annual emissions could cause the 16% increase in CO_2 flux into the ocean.

Note: The amount of CO_2 removed after the eruption could be considered to be 10 Gt (1.2 ppm), half of what is discussed here. The fact that CO_2 is being dissolved from the atmosphere into the ocean at a rate proportional to the difference between the CO_2 level and the ice-age average of 180 ppm suggests that of the 20 Gt emissions in 1992, 10 Gt were removed by dissolving into the ocean and land, and the remaining 10 Gt were removed with eruption-related mechanisms, arguably OIF.

El Nino events correlate with short-term CO_2 variations

Variations in the atmospheric CO_2 level increase generally correspond with El Nino and La Nina events. The 1990-1992 El Nino event had a magnitude similar to the 1987 event, which corresponded to a CO_2 level increase of 0.8 ppm. If there had been no El Nino, CO_2 levels might have decreased 0.3 ppm year-by-year in 1993.



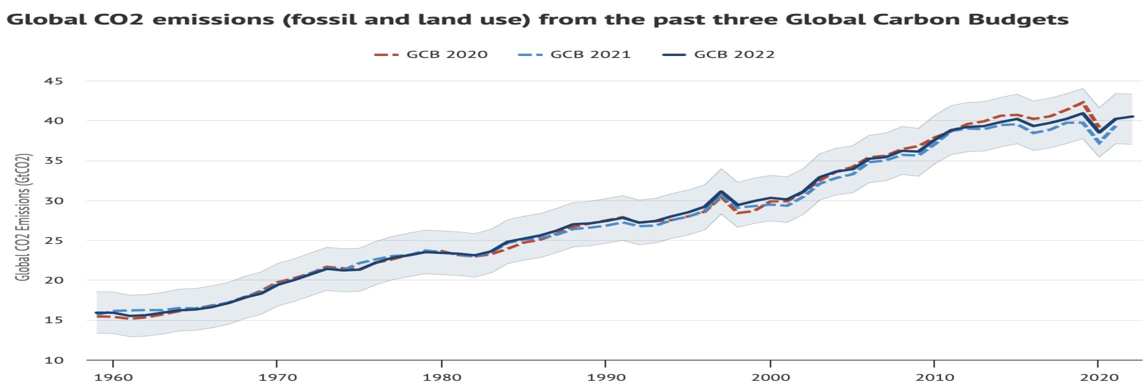
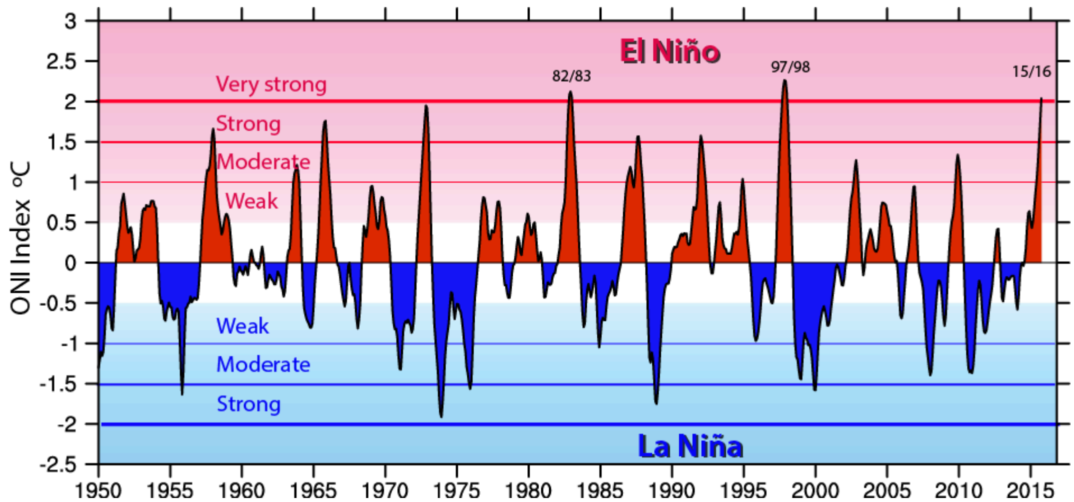


Figure 5. Annual CO2 increase, 12 month average, with parabolic trendline showing CO2 increase of 1.5 ppm per year in 1985, 1.75 ppm /yr in 1995, 2.0 ppm / yr in 2005, and about 2.5 ppm / yr in 2020. https://keelingcurve.ucsd.edu/permissions-and-data-sources/ CO2 emissions growth matches the CO2 ppm / year growth from 1975 to 2022 (Carbon Brief graph, using Global Carbon Project data)

CO2 levels increased at a steadily increasing rate during the 1975 to 2020 period, corresponding to increased population (21% growth), GDP (107% growth) and emissions (15% growth). There is also a strong, short-term (two-to-five year) variation that generally corresponds to the El Niño/Southern Oscillation (ENSO) cycle. El Niño explains much of the short term variation in the steadily increasing CO2 increases. This data indicates that the 1992 CO2 removal was not caused by El Niño. El Nino events are usually associated with temporarily increased CO2.

If the 1991-1994 El Niño had not occurred, we might expect that the annual CO2 increase would have been 0.75 ppm / year lower, resulting in a reduction in measured CO2 level in 1992.



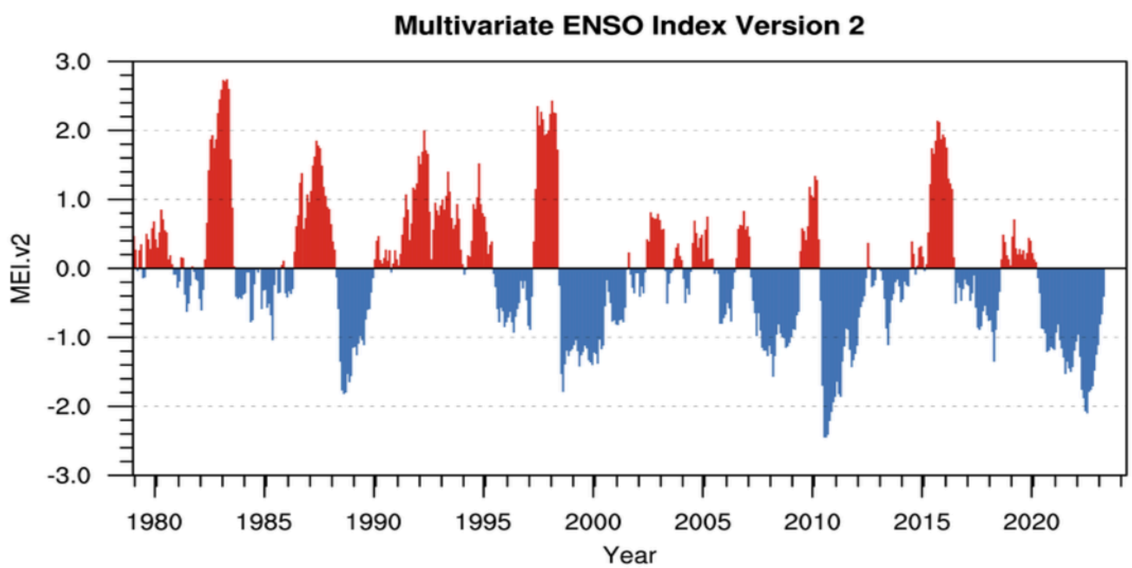


Figure 6. El Niño (in red) and La Niña (blue) indicator data from NCAR and NOAA: https://psl.noaa.gov/enso/mei/
https://www.weather.gov/tbw/tampabayelninopage

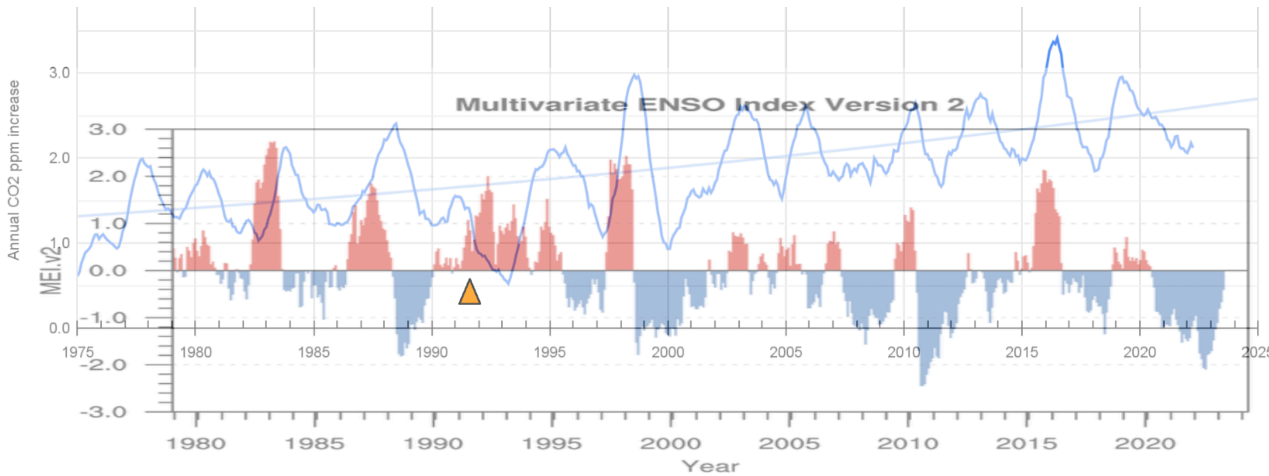


Figure 7. Annual CO_2 increase with El Niño and La Niña indicators, showing the correlation between CO_2 increases and El Niño events. The El Niño in 1992 was of magnitude similar to 1987, in which CO_2 increased 0.75 ppm / year above baseline. Without the El Niño event, the CO_2 dip in 1992 might have been 0.75 ppm lower.

Conclusion

- Analysis of atmospheric CO_2 concentration ("Keeling curve") data indicates that 2.3 ppm of CO_2, corresponding to 20 Gt were removed for at least a decade in the year following the 1991 Mt. Pinatubo eruption. This is roughly the same as reported global CO2 emissions that year.
- The 2.3 ppm annual reduction in CO_2 coincidentally roughly matches recent 2.3 ppm annual CO_2 increase. Triggering a similar OIF process intentionally could allow us to achieve net-zero emissions in the near future. Tripling it would allow us to restore pre-industrial CO_2 levels by 2050.
- Alternate CO_2 removal explanations have been proposed, but they don't explain the magnitude or duration of the observed CO_2 removal. They relate to increased photosynthesis on land and cooled ocean water absorbing more CO_2. These mechanisms would produce short-lived removals of less than 1 Gt lasting just 1-2 years.
- The collapse of the USSR in December 1991 led to emissions reduction of roughly 0.4 Gt CO_2, varying between sources. This is roughly 2% of the observed CO_2 removal.
- Current OIF theory could be updated to include the ability of cyanobacteria to fix nitrogen as needed when iron levels are high and sustained over months. Current theory indicates that there are not enough macronutrients in the ocean to remove more than 1 Gt C, or 3.75 Gt CO_2 per year. The fact that five times that much CO_2 was removed from less than 1% of the ocean suggests that the required macronutrients were supplied by some mechanism.

- The volcanic ash rich in apatite may have supplied the required 50 Mt [13] phosphorus. The phosphorus content of volcanic ash varies from 0.1% to 1% by volume (Deer et al. 1992). Cyanobacteria may have provided the required nitrate. Price 1991[14] indicates that nitrogen fixing bacteria (blue-green algae) require about 20 times more iron than algae. Thus the nitrogen fixing bacteria may have provided the needed nitrogen. These new hypotheses regarding nitrogen and phosphorus have not been tested.

- Although OIF cannot be proven to be the primary source of the CO2 removal in 1992, the lack of other explanations that fit the data justifies an interim testable conclusion that natural OIF was the cause. Considering the urgency of global warming and the fact that no undesired side effects of natural or intentional OIF have been reported to date, immediate efforts to intentionally replicate and scale natural OIF is justified.

- CO2 removal by OIF as high as 20 g C m^{-1} day^{-1} has been reported (Danieri et al. 2000). This is equivalent to .66 Mt CO2 km^{-2} $year^{-1}$. To remove 60 Gt CO2 / year might require 10^5 km^2 of high productivity downwelling eddies, about 0.3% of the ocean area. This could be accomplished with 10 eddies 355 km in diameter, or 32 eddies 200 km in diameter.

- The benefit / cost ratio of doing the test and scaling up is about 10,000 to 1. The projected cost over 50 years of not pursuing replication ($250 trillion in ecosystem and economic system damage) is roughly four million times more than the cost of a replication program ($25 billion, Appendix A, below). Millions of years of natural OIF and 13 tests since 1990 have produced no reported harmful side effects.

- The authors recommend developing plans to scale OIF up to the needed level, and to perform tests to optimize performance while validating safety in the next 2-3 years. Humanity needs to restore historically safe CO2 levels, below 300 ppm, while its ecosystems, social systems, political and economic systems are sufficiently intact, by 2050. No other proposed CO2 removal pathway can scale up fast enough to avoid the projected $150 trillion economic cost, plus unpriced ecological and cultural losses.

Appendix A: A Pinatubo Pause Replication Project

Consistent with the need to remove 50 to 100 Gt CO2 / year in order to restore safe CO2 levels by 2050, a CO2 pause replication project either in the Pinatubo eruption ash fall area or a similar area is proposed to rapidly optimize engineering parameters for maximizing CO2 removal (CDR) and fishery benefits[15]. Development and at-scale operation is intended to be philanthropically funded,

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[13] The Redfield ratio indicates that a ton of phosphorus is required per 106 tons of C or 392 tons of CO2.
[14] Iron Nutrition Of Phytoplankton And Its Possible Importance In The Ecology Of Ocean Regions With High Nutrient And Low Biomass; Oceanography V4 #2 1991
https://pdfs.semanticscholar.org/4a20/9a6541ea5b925257f83ae65e600ac364991d.pdf

[15] African desert dust influences migrations and fisheries of the Atlantic skipjack-tuna

avoiding political issues. CO_2 removal is to be measured using low-cost buoy based and satellite based atmospheric CO_2 level detection.

This engineering project would run in parallel with ExOIS ocean science projects in the Gulf of Alaska and Southern Ocean. These tests are expected to require ten years to complete at a cost of roughly $100 million. They are designed to develop a roadmap to profitably remove 1 to 4 Gt CO_2 / year across much of the world's ocean.

The engineering test would monitor atmospheric CO_2 (which impacts climate) with buoy data confirmed by NASA OCO-2 satellite data and Mauna Loa NOAA data. These measurements would complement conventional oceanographic research projects.

The research goals for the Pinatubo CO_2 pause replication test are:

1. Demonstrate that ocean-based OIF with CO_2 measurement can be funded and performed: politically, socially, financially and practically.
2. Validate the down-welling eddy hypotheses by running a control outside an eddy.
3. Validate the nitrogen fixing hypothesis, measuring cyanobacteria and nitrate levels.
4. Use satellite and buoy CO_2 measurements to quantify longer-duration sequestration.
5. Optimize a nutrient protocol to a) maximize CO_2 removal (short term) in the downwelling eddy and reproduce the multi-month CDR activity observed in 1991-1993.
6. Measure, optimize and publicize fishery benefits of OIF

Plans call for an engineering scale-up from 100 km square region to roughly the 300 km diameter of the eddy over several years. The test area would be divided into a 4x4 grid of 25 km cells allowing simultaneous testing and optimization of 16 protocols. By using real-time CO_2 data from buoys and satellite data, productivity can be optimized rapidly. The CO_2 and fishery productivity would be measured over a range of periods from one week to two years. Confirmation of long-term CO_2 removal will require several years of follow-up data from the buoys, satellites and Mauna Loa (Keeling curve).

1. Assemble the operational structures (performed in parallel)
   - Develop a Philippine OIF project team with funding
   - Develop the operational plan for a 100 x 100 km test, divided into sixteen 25 km test regions, with CO_2 measurement buoys at the intersections of the regions.
   - Assemble an ethics panel of representatives from stakeholder groups (CRSGB)
   - Develop CO_2 measurement buoys and recipe optimization protocols.
   - Invite research groups to take scientific data from this engineering project. (ExOIS)
2. Operate a "minimum viable product" (MVP) OIF design.
   - 100 km square test using varying concentrations of iron sulfate, iron oxide and phosphorus
   - Apply for permits and MOUs as appropriate
   - Deploy buoys to measure CO_2 and wind
   - Rent a suitable ship and sensor vehicles (gliders and / or uncrewed ship)

    ○ Optimize the process over six one-month applications
3. Safely expand the 100 km pilot to 200 and then 300 km as is warranted.
4. Replicate the project in other promising ocean regions as appropriate.

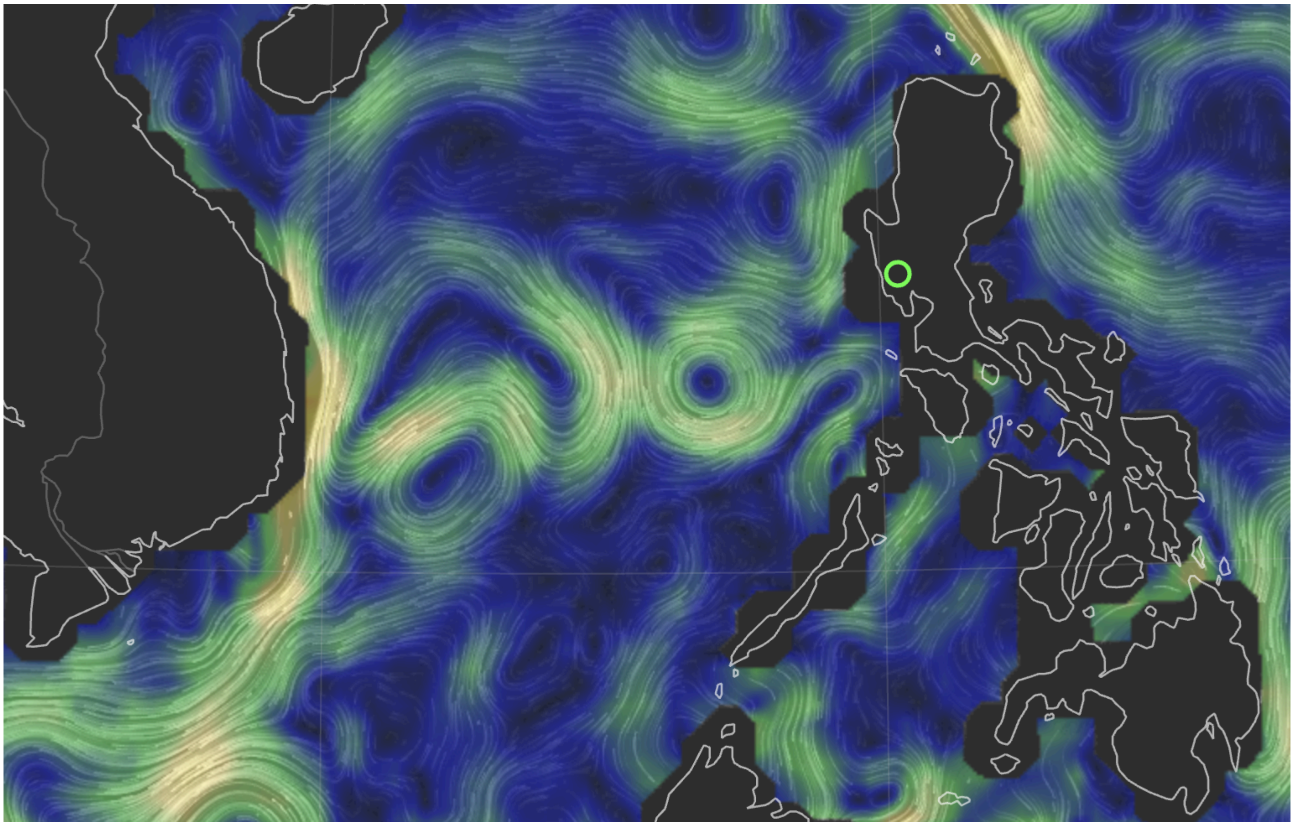
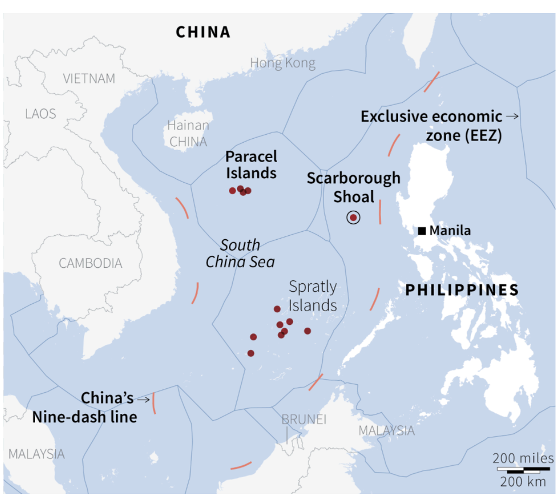


Figure 8. A persistent ocean eddy, 350 km diameter, is visible 440 km WSW of Mt. Pinatubo (green circle). The eddy is downwelling (anticyclonic, clockwise rotating). This is where much of Pinatubo's fine volcanic ash settled. From Earth.nullschool.net



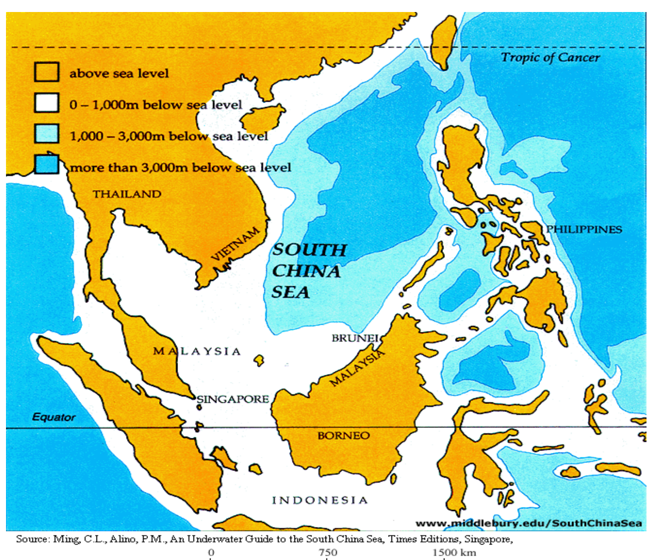


Figure 9. Exclusive Economic Zones and ocean depth in the region of the Pinatubo ash fall. The eddy is generally inside the Philippine EEZ.

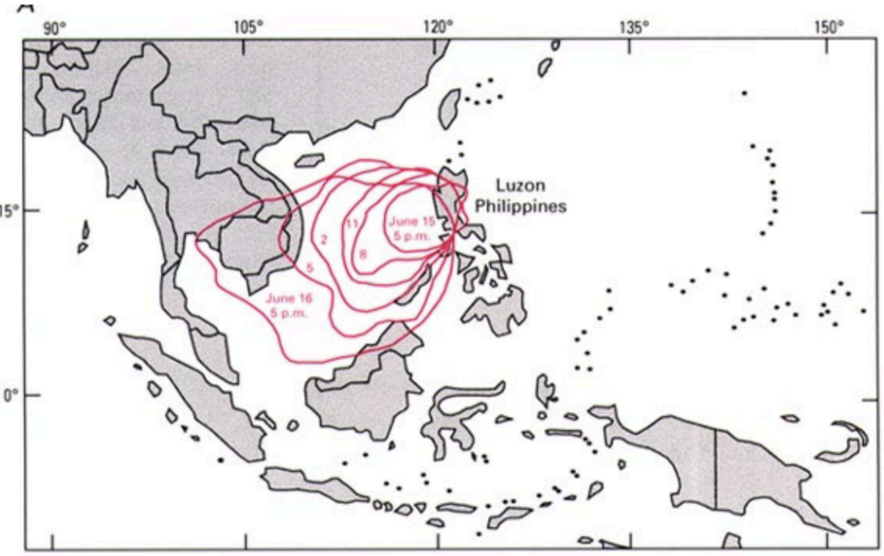


Figure 10. Pinatubo eruption cloud in the 24 hours following the main eruption. Ash was no longer visible after June 16. The vast majority of ash fell in the June 15 5pm circle. (Self 1999)

Appendix B: Four other eruptions since 1880 that cooled the planet show no CO2 removal where no down-welling eddy is nearby

The 1963-64 Agung volcano eruption led to cooling similar to the Mt. Pinatubo volcano (fig. 11). It was followed by only temporary CO2 removal. The CO2 removed appears to have returned to the atmosphere over the following year, perhaps because there was no down-welling eddy nearby. There are no eddies near Bali because it is close to the equator.

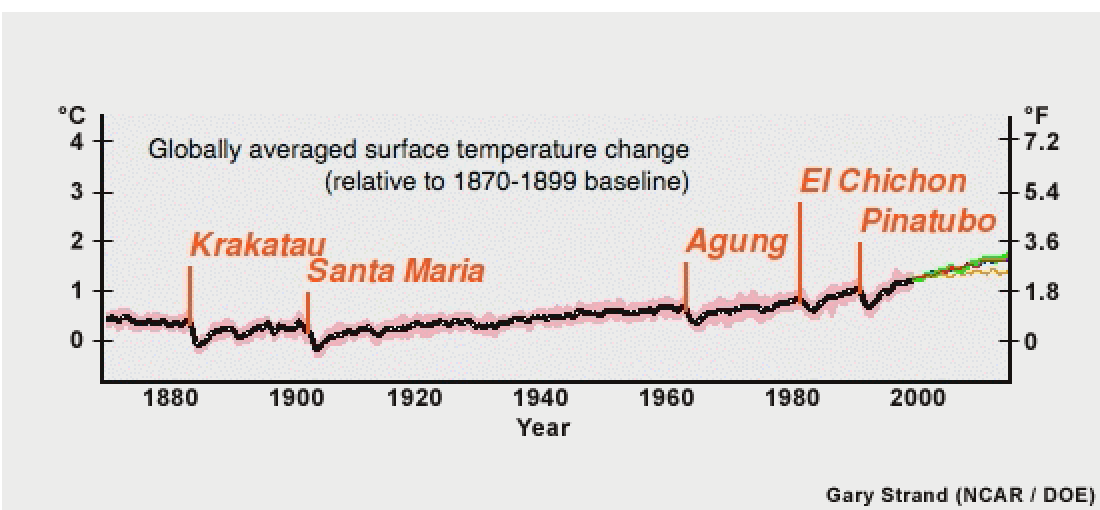


Figure 11: Global average temperatures showing the impact of major volcanoes. NCAR

Fig 12 shows that the Agung and El Chichon eruptions show no CO2 reduction. Winds were blowing westward, with the nearest coast about 700 km downwind. Thus little ash is likely to have reached deep ocean areas. Agung, on the island of Bali, near the equator, has no eddies nearby and also produced roughly zero net CO2 removal after a year.

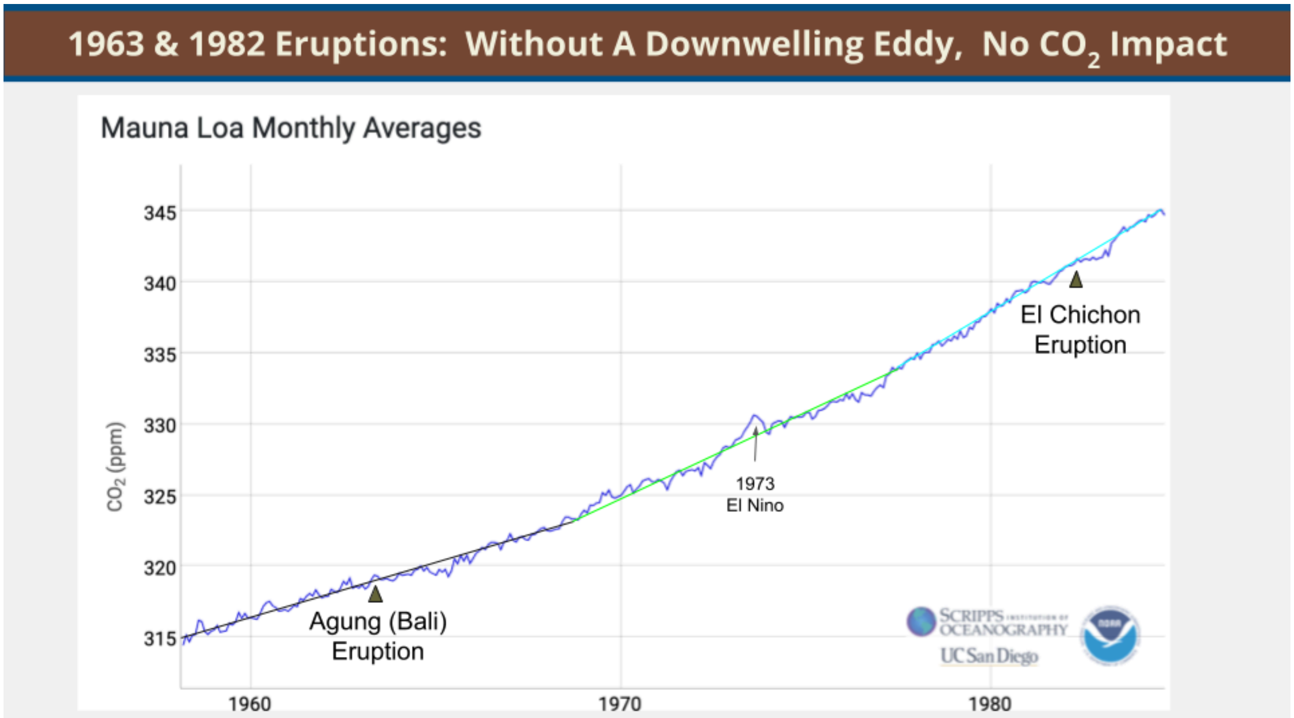


Figure 12: Average CO2 levels at the end of 1964 were 0.6 ppm lower than would be expected based on trends five years earlier and later. CO2 returned to baseline from mid 1965 through 1969. It is possible but speculative to conclude that this resulted from the 1963-64 Agung eruption.

Eruption	Year	Temp. reduction	km^3 of rock released	CO_2 ppm reduced after 10 years,	Eddy near ash fall?
Pinatubo	1991	0.5 °C	5	2.3	Yes
El Chichon	1982	0.4 °C	1	0	No: landlocked
Agung	1963	0.2 °C	1	0	No: equatorial
Santa Maria	1902	0.2 °C	5	0	No: landlocked
Krakatoa	1884	0.6 °C	21	0	occasional
Tambora	1815	0.5 °C	40	6	Yes

Long Island PNG	1660	0.5 °C	21	0	No: equatorial
Huaynaputina	1600	0.5 °C	35	0	No: 120 km from coast
Billy Mitchell	1580	0.2 °C	14	11	Yes

Table 2. Ppm per year from NASA. Krakatoa difference measured 1874 to 1884 and 1884 to 1894

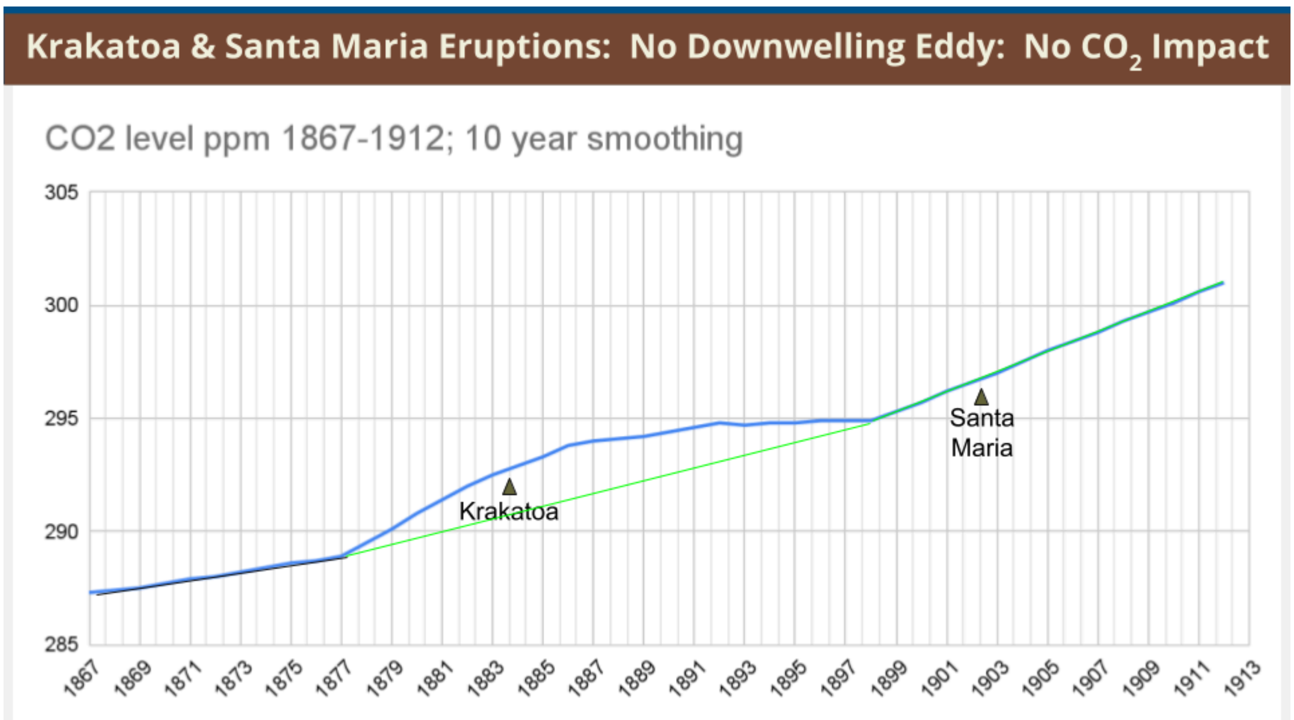


Figure 12a. Ice core based CO2 levels around the Krakatoa and Santa Maria eruptions. The surge around 1887 could indicate 20 Gt CO2 emission along with the 25 Gt rock release. NASA Ice core data with 10 year smoothing

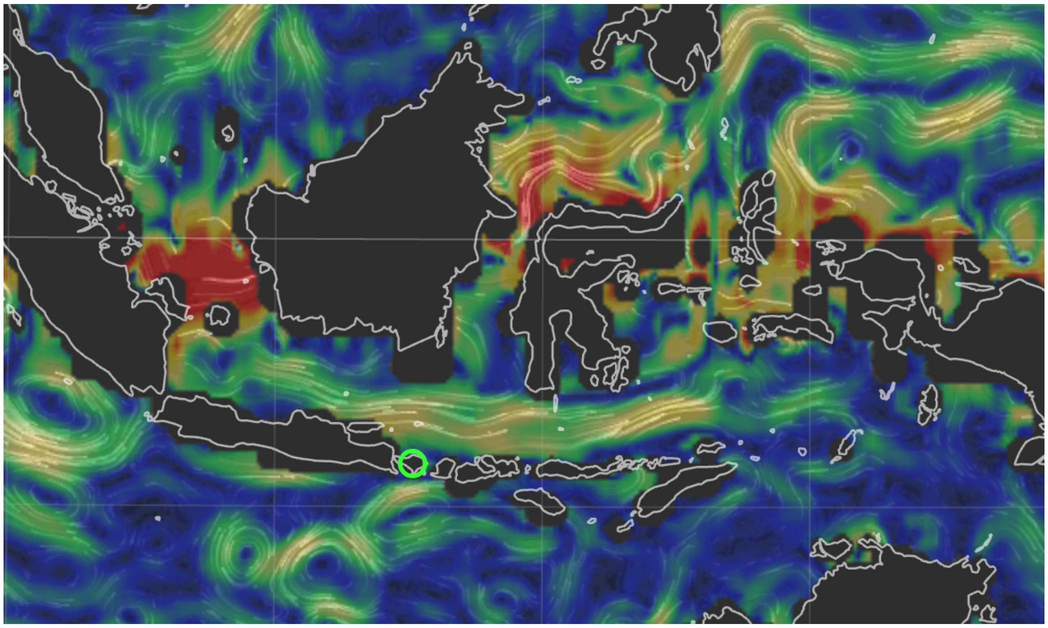


Figure 13. [Ocean currents near Bali](), (green circle) at 8 degrees South, have few if any eddies, suggesting that the biocarbon produced, which reduced CO2 by 0.6 ppm for 6 months, stayed near the surface where it was subsequently consumed and metabolized by fish and other animals.

The Tonga 2022 eruption removed CO2 for just 4 months

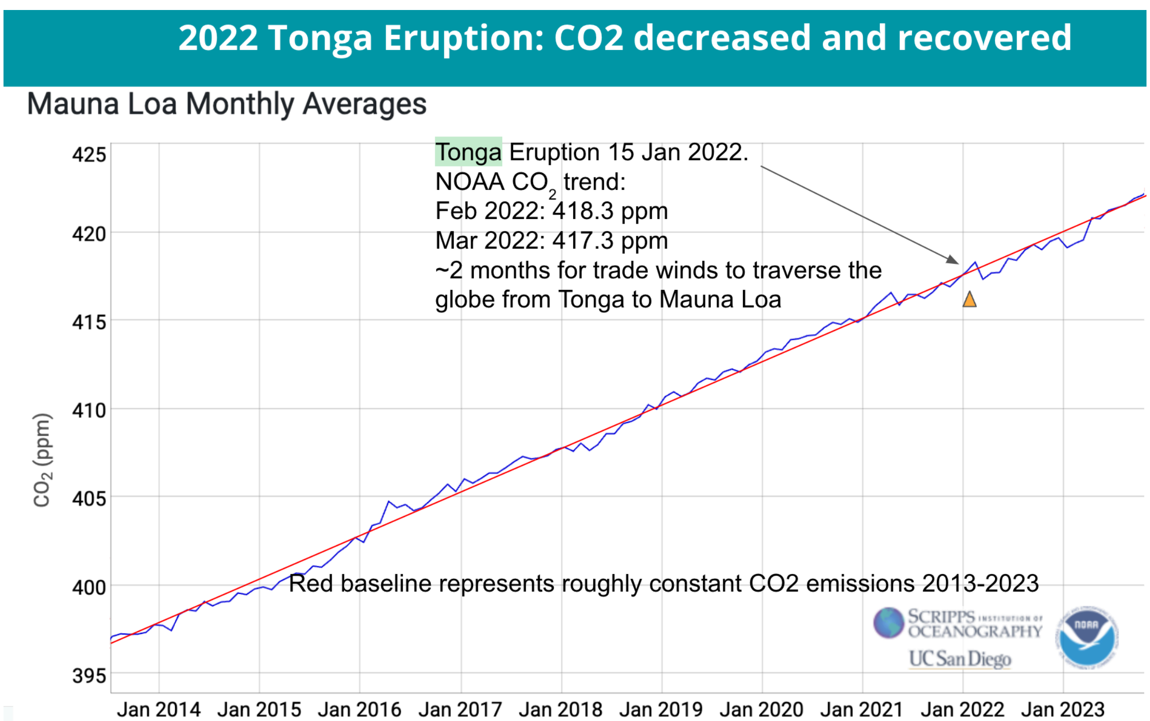
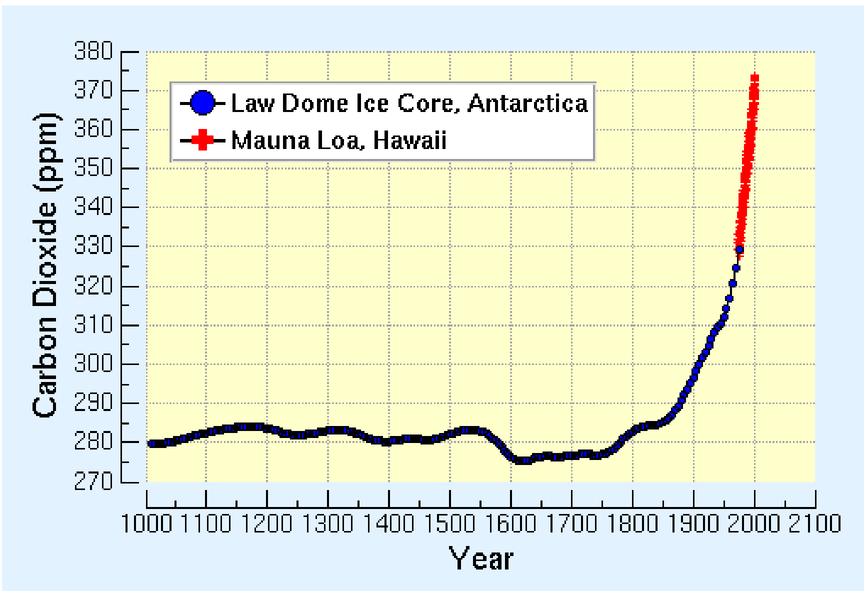


Figure 14. Following the January 2022 Tonga eruption, Mauna Loa data recorded a 1 ppm drop between February and March. This may represent an air mass of low CO_2 that traversed the globe with trade winds in 2 months and dissipated by June.

If the air mass with 1 ppm CO2 reduction was 1% of the Earth's area, it would represent roughly 100 Mt CO2, or an undetectable 0.01 ppm after mixing through the atmosphere. There were no significant downwelling eddies in the vicinity at that time.

CO2 removal following the 1580 Billy Mitchell and 1815



D.M. Etheridge, L.P. Steele, R.L. Langenfelds, R.J. Francey, J.-M. Barnola and V.I. Morgan. 1998. *Historical CO2 records from the Law Dome* DE08, DE08-2, and DSS ice cores. In *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

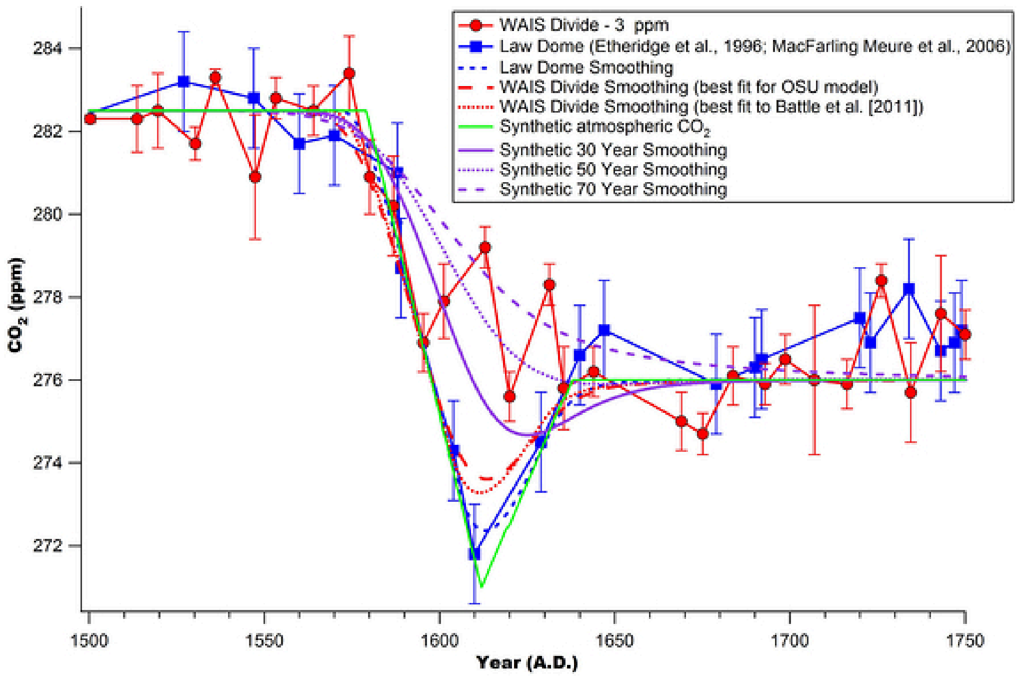


Figure x Open in figure viewerPowerPoint Smoothing an imaginary atmospheric CO_2 time series (green line). The synthetic atmospheric CO_2 time series has slightly larger decrease of CO_2 than Law Dome records at ~1600 A.D. To better compare magnitude of CO_2 decrease at ~1600 A.D., we subtracted 3 ppm of CO_2 concentration from WAIS Divide core record (blue line) and compared with three synthetic smoothing curves (purple lines).

Appendix C: Plan A for restoring safe CO2 levels

While it may generate future scientific insight, the Pinatubo Pause is especially significant to the field of climate restoration. The fact that nature randomly caused a removal of 20 Gt of CO2 in a year following an eruption, suggests that careful optimization of ocean fertilization could produce the same or more removal in an attempt to ensure Earth remains habitable for humanity and today's ecosystems.

When priority is given to restoring a historically safe climate for humanity flourishing, we have ranked the available solutions, and OIF is Plan A. This is because of its low risk, low cost, high speed and ease of implementation. Given that there have been no reported detrimental side effects of OIF, either natural or intentional, scale-up studies could be financed by groups committed to restoration.

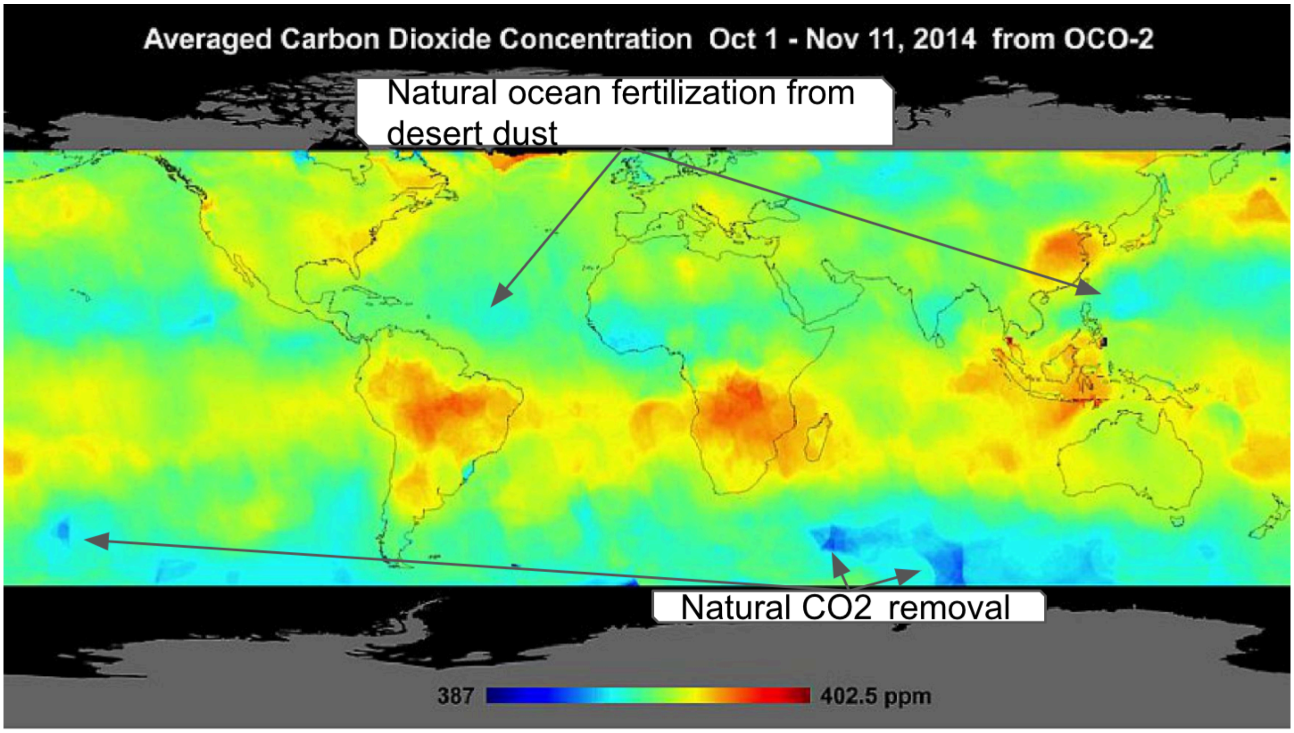


Figure 14. Satellite CO2 data averaged over 6 weeks in 2014 shows regions of natural OIF (blue regions). In the Southern Ocean the fertilization is thought to be from upwelling and volcanic sources. Dust blown from the Sahara and Gobi (China) deserts may provide fertilization in tropical regions.

The next best scalable, permanent and financially viable CO2 restoration option, synthetic limestone, costs almost 100 times more per ton of CO2 removed and would predictably take several decades to scale up (see [Working Paper on CDR cost comparisons)]. Well financed CDR methods such as Ocean Alkalinity Enhancement and Direct Air Capture are more than 10,000 times more expensive per ton of CO2 removed (both cost and energy). Running any of these methods at scale would require someone budgeting more than ten times global military spending over many decades[16]. Thus urgent testing and scale-up of OIF appears today to be the best and perhaps only way to ensure the survival of future generations.

According to the iron hypothesis, one ton of iron promotes photosynthesis that removes as much as a million tons of CO2 from the atmosphere and transports it into the ocean depths as the plants, grazers, and other sea life die and sink. Therefore removing 60 Gt CO2 per year, 3 times more than following the Mt. Pinatubo eruption would require application of 60,000 tons of iron, likely in the form of iron sulfate. The cost of iron sulfate might total $5 million per year.[17] Early, unoptimized OIF studies suggested that 10 - 100 times more iron might be required. If optimization fails, material

[16] Currently operational direct air capture costs $1000 per ton; entrepreneurs expect it to drop to $600 / ton by 2030. Removing 60 Gt per year at the hoped for cost would total $36 trillion— 25% of global GDP.
[17] Ferrous sulfate cost of $60 to $100 per ton.
https://www.made-in-china.com/products-search/hot-china-products/Ferrous_Sulfate_Price.html

costs might become \$50 or \$500 million—still thousands of times less than estimated costs of novel CDR methods such as direct air capture (DAC) or ocean alkalinity enhancement (OAE).

We extrapolate that intentional OIF can plausibly withdraw 60 Gt of CO2 (7 ppm) per year safely and thereby restore CO2 levels below 300 ppm by 2050 at an annual cost below \$1 billion / year.

Appendix D: How many eddies are needed to remove 60 Gt CO2 / year?

A lower bound estimate is that 22 downwelling eddies, 360 km, constituting 0.6% of total ocean area could remove CO2 at the rate needed to restore safe CO2 levels by 2050.

We need to remove 1200 Gt CO_2 over 20 years (60 Gt CO_2 / year) to restore CO_2 to historically safe levels by 2050. Observed natural OIF has been observed to remove 20 g C/m^2/day (Danieri et al. 2000). That means that 2.2 million km^2 of ocean out of the 360 million km^2 ocean area is sufficient to remove the needed CO2 (calculation below). That is, 0.6% of total ocean area is required. If each eddy is 100,000 km^2 (roughly 360 km diameter), that requires 22 eddies.

Calculation

20 g C/m^2/day X 3.7(mw CO2 / mw C) X 365 day/year X 10^{-9} ton/g X 10^6 m^2/km^2 = 0.027 Mt CO_2/km^2 / year.

60,000 Mt CO_2/ year / 0.027 Mt CO_2/km^2 / year = 2.2 million km^2
Earth's oceans cover 360 million km^2
2.2 million km^2 / 360 million km^2 = 0.006 of ocean area, or 0.6%

Revision history

10 March 2024: Updated the summary to specify that no other existing hypothesis can satisfy the data.

15 March 2024: Moved "Options for restoring a safe climate" to Appendix 3

4 May 2024: Added note of trace ash deposit in Vietnam, and extrapolating to insufficient iron addition to impact land or ocean photosynthesis beyond the South China Sea.

18 June 2024: Added table 1: 10-year average CO2 increases, showing steady increase between 1980 and 2015 if one assumes that the Pinatubo pause was caused by permanent CO2 sequestration in the deep ocean.

3 August 2024: Added nitrogen fixing hypothesis

7 March 2025: Added abstract and calculation of # eddies to restore safe CO2 levels by 2050