Implementing Climate Restoration This Decade

David M. Snyder, P.E.
42TEK LLC
Campbell USA
david@42tek.com

Peter Fiekowsky
Climate Restoration Program
Los Altos USA
pfieko@gmail.com

***Abstract*—In parallel with achieving zero net emissions of carbon dioxide (CO_2), the world needs to reduce current levels in the air of above 420 ppm to historically safe pre-industrial levels below 300 ppm. Atmospheric restoration using ocean iron fertilization (OIF) to stimulate phytoplankton uptake of CO_2 in strategic areas of the ocean appears to be the most effective option to achieve climate restoration to ensure a safe environment for posterity. This is based upon historical CO_2 data related to ice ages and the effects of eruptions, especially the 1991 Mt. Pinatubo eruption. A pilot project with modern measurement, reporting, and verification technologies, including instrument buoys and satellites, will help to confirm the approach and refine its methodology.**

Keywords—climate, atmosphere, carbon dioxide, phytoplankton, iron, measurement

I. Introduction

Dealing with global warming due to Greenhouse Gases (GHG) and associated environmental damage and economic losses is now an important societal issue. The scientific basis has been understood for more than 100 years. [1] Although the United Nations Framework Convention on Climate Change (UNFCCC) predicts global warming progress over coming decades and centuries under a range of scenarios, there is currently no international organization tasked with defining and implementing solutions that will protect biodiversity in the ecosystems that allowed the development of agriculture and the diversity of human civilizations around the world. [2] This paper lays out, from an engineering perspective, a pathway to climate restoration and critical milestones.

Climate restoration and associated actions of restoring historically safe CO_2 and methane levels in the atmosphere are the goal. It focuses on CO_2 and methane levels because they are the direct drivers of global warming.

Fig. 1 shows temperatures and CO_2 levels during the last 800 thousand years (shown as 800 kiloyears (ky)) from Jouzel et al relative to the mean temperature of the last 10 ky and Dome C CO_2 levels from Luthi et al. (kyBP is kiloyears before present) This shows the 100 to 130 ppm decrease in CO_2 levels (equivalent to roughly 1,000 Gt CO_2) that occurs before ice ages. The close correlation between CO_2 and temperature indicates that without restoring safe CO_2 levels, achieving a historically safe climate is unlikely. [3] [4] [5]

The terms "mitigation" and "adaptation" have been used to describe methods to reduce emissions or learn to live with global warming. [6] To recover and maintain biodiversity that our civilization is based on, "restoration" of the atmosphere and thus

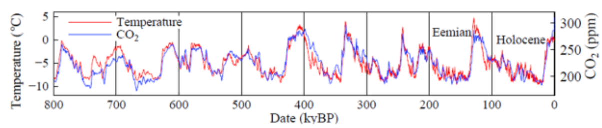

Fig. 1. Antarctic Dome C temperature for past 800 kiloyears [3]

the climate is required. Restoration is defined as recovering Holocene or pre-industrial CO_2 levels.

Dozens of other factors, including clouds, aerosols and ice cover are involved and are being researched. Only with the restoration of Holocene CO_2 levels will influencing those factors have a significant impact on humanity and biodiversity.

Methane constitutes 20% of the "forcing" that causes global warming. Its removal is important to humanity and ecosystems due to the risk of a repeat of the Paleocene-Eocene thermal maximum (PETM) methane burst that caused 30% of species to become extinct. [7] However, for the purpose of this paper we will focus on CO_2, reserving discussion of what needs to be done with respect to methane until later.

CO_2 and methane emissions control (i.e., zero emissions) is not enough to reverse global warming. The world needs to remove substantial amounts of CO_2 from the atmosphere to get from the current level of approximately 420 ppm down to 300 ppm or less, as existed in pre-industrial times (see Fig. 2). What do we mean by substantial amounts?" To accomplish climate restoration, we need to remove over 1,000 gigatons of CO_2 from the atmosphere. This works out to 60-75 gigatons per year (Gt/yr) for 20 years, from 2030 to 2050, including expected new emissions. Then, between 2050 and 2100, removing about 30 Gt/yr would get CO_2 back to 280 ppm, and warming back to zero degrees. [8]

Climate modeling using the MAGICC model (Model for the Assessment of Greenhouse Gas Induced Climate Change), used in recent Intergovernmental Panel on Climate Change (IPCC) reports, shows that removing net 60 Gt/yr CO_2 will bring CO_2 levels to 300 ppm by 2050, and global warming back to 0.75 degrees C. Continuing removals could restore pre-industrial temperatures by 2100. In Fig. 2, past data is historical, and future data is modeled. The 1991 Pinatubo eruption is visible in the CO_2 graph and an 18-month cooling in the temperature graph. [9]

Ocean iron fertilization (OIF) can be done in a way that emulates what has occurred in nature over a long period of time and appears to have been repeated more recently following the 1991 Mt. Pinatubo eruption. A pilot study based upon our scientific understanding will confirm this approach.

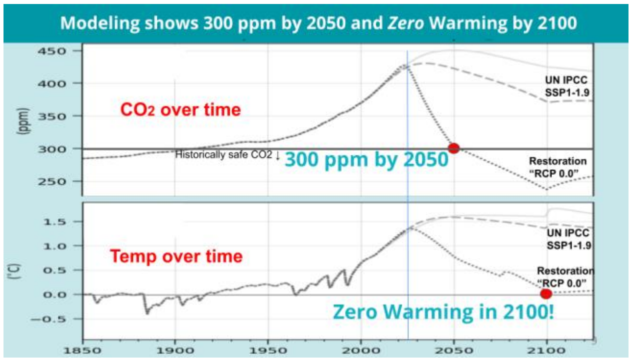

Fig. 2. MAGICC modeling of IPCC and climate restoration pathways.

II. Natural Processes Can Achieve Both Large-Scale and Rapid CO_2 Removal

A. *Background on ocean iron fertilization (OIF)*

Our hypothesis is that powerful natural, ocean-based processes can be replicated intentionally to restore a safe climate.

The CO_2 record in Fig. 2 shows that leading up to ice ages, roughly 1,000 gigatons of atmospheric CO_2 (equivalent to 130 ppm) were removed and sequestered in marine environments. They remained stored in the ocean as carbonates for about 50,000 years. The quantity of dissolved carbonates in the ocean would have increased by 1-2%.

The iron and a fraction of the removed carbon fell to the ocean floor, providing the historical record. After thousands of years, at the end of the ice age, those carbonates were converted back to CO_2 and released to the atmosphere.

This process was discovered and reported by Martin 1990 as the "iron hypothesis," which the National Science Foundation later portrayed as one of the most notable discoveries of the 20th century, summarized as follows. An increase in dust storms over the ocean leads to increased phytoplankton growth. Plankton photosynthesis captures large-scale amounts of CO_2 and deposits on the seafloor layers provide evidence of this. In addition to dust storms, iron is replenished by volcanic activity, ocean upwelling, and whale feces. [10] [11] [12] [13]

Today, most of the deep ocean appears blue, indicating low rates of photosynthesis and phytoplankton. Far offshore, iron is often a millionth of coastal concentrations, as iron tends to sink.

Numerous laboratory and ocean tests have shown that intentional replenishment of trace amounts of iron in low-chlorophyll regions stimulates phytoplankton growth. The growth continues until other nutrients, usually nitrates and phosphorus become depleted, becoming limiting factors. If photosynthesis is to be sustained, they, in turn, must be replenished.

Nitrogen is required for the growth of all plants, and in the ocean it is preferentially supplied by nitrogen-fixing bacteria (usually Trichodesmium). In marine environments, cyanobacteria fix nitrogen and replenish nitrates, but they require iron concentrations 10-20 times higher than phytoplankton to grow. [14] [15]

Trichodesmium also grows more slowly than most phytoplankton, commonly requiring months to produce a bloom, compared to days to produce a phytoplankton bloom. Providing enough iron, for a long enough period of time, for both phytoplankton and cyanobacteria to grow, could, hypothetically, produce a long-duration phytoplankton bloom consistent with the 1992 CO_2 data related to the Mt. Pinatubo volcano eruption discussed in the next section (Fig. 3). We call this process nitrogen ocean iron fertilization (N-OIF).

B. *The Pinatubo CO_2 pause*

Mt. Pinatubo, near Manila in the Philippines, erupted in June 1991. It was followed by a well-known global cooling event that lasted about 18 months, caused by sulfur aerosols sprayed into the upper atmosphere. Those aerosols reflected a few percent of sunlight back into space, shading and slightly cooling Earth by about 0.5 degrees C.

Separate from the aerosols and cooling, several billion tons of volcanic ash landed in the ocean and probably provided abundant iron for the growth of phytoplankton as well as nitrogen-fixing cyanobacteria, especially Trichodesmium.

In Fig. 3, the Mt. Pinatubo eruption is designated with a yellow triangle. The increase in the CO_2 level before the eruption is followed by a significant reduction, a resumption of CO_2 increase, and then a 14-month stable period. It took approximately 40 days for CO_2 changes near Mt. Pinatubo to blow Westward three-fourths of the way around the planet to the Mauna Loa observatory in the upper-level trade winds. [16]

Much of the ash from Mt. Pinatubo is reported to have fallen in the location of a large, persistent, downwelling and converging ocean eddy centered about 150 km downwind, west-southwest of the volcano. The ocean is 3 km deep in that area.

Downwelling occurs when ocean currents form an anticyclonic (clockwise in the northern hemisphere and counterclockwise in the southern) eddy. These eddies can be hundreds of kilometers in diameter and persist for varying amounts of time, depending on changes in currents and wind.

Downwelling eddies transport water from near the surface to the depths of the ocean.

It appears that the downwelling of the eddy downwind of the Mt. Pinatubo volcano contributed to sinking a large amount of biocarbon, particularly from the zooplankton (animal

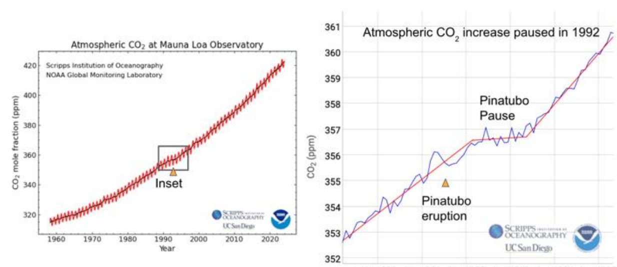

Fig. 3. NOAA Atmospheric CO_2 levels from Mauna Loa, 1957-2024, and 1989-1996. [16]

plankton), which consumes much of the phytoplankton during the night. Zooplankton commonly feed on surface phytoplankton at night and then swim to dark depths below several hundred meters during the day to avoid predators and digest their 'meals.' The fecal matter they produce at those depths, where the downwelling is strongest, will often sink further still and avoid being consumed by the food chain.

In other words, the downwelling effect could explain the extraordinary long-term removal of 20 Gt CO_2 in 1992. The same effect is not associated with other large eruptions, such as Agung (1963) and El Chichon (1980). [16] Although these volcanoes produced cooling events visible in Fig. 2, their removal of CO_2 was neither as large nor as long-lived as the Pinatubo Pause shown in Fig. 4.

In Fig. 4, long-term CO_2 levels continue to increase, with a slope proportional to net emissions, modulated mainly by eruptions and El Nino events. In the decade before and after the Mt. Pinatubo eruption, CO_2 levels increased steadily, notwithstanding the 20 Gt decrease after the eruption. The 1998 El Nino is notable, but its net CO_2 effect appears to average out to zero over the 3 years before and after it. [17]

C. An engineering approach to solving climate disruption

Most academic literature on climate change applies a scientific lens, measuring and understanding the past and then predicting the future, assuming nothing changes. Technological solutions are designed to fit into that scientific model.

In contrast, an engineering approach carefully defines the challenge and proposes the development of a currently viable "baseline" solution. Over time, potential new solutions can compete with the baseline solution.

What follows is an engineering roadmap for solving the climate challenge.

1) Define the problem and solution

   Stakeholders in the future of humanity are concerned about the well-being of future generations as global warming impacts become more severe. Some stakeholders are interested in restoring a historically safe climate.

   The solution is to remove excess CO_2 and restore the pre-industrial (Holocene) climate that supported agriculture, civilization, and biodiversity for 12,000 years. This climate in which humanity flourished is characterized by CO_2 levels below 300 ppm.

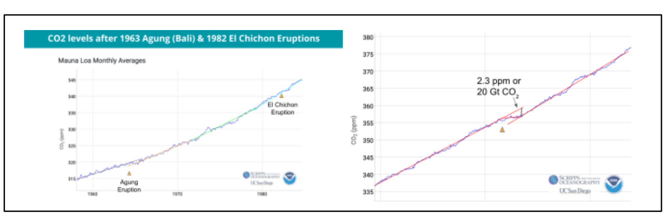

Fig. 4. CO_2 Trends around Agung, El Chichon, and Mt. Pinatubo eruptions [17]

2) Define a specific, measurable goal

   Atmospheric CO_2 levels have been reliably measured for decades. CO_2 levels are directly changed by adding or removing CO_2. Today's political and scientific goal is to "try to keep warming below 1.5C." Yet this cannot be measured because "trying" is not quantitative. Furthermore, measuring global average temperature is complex and depends on assumptions that change over time and between institutions.

3) Focus on a specific method to achieve the goal to serve as a benchmark for performance.

   The method is preferably one that has already been proven to work safely.

   a) In this case, natural processes are known to have safely removed the desired amount of CO_2 many times in the last million years during the ice age cycle. The specific process is OIF. OIF boosts photosynthesis in the ocean by replenishing trace amounts of iron for phytoplankton growth.

   b) In addition, the "Pinatubo Pause" of 1992, during which roughly 20 Gt of CO_2 was removed from the atmosphere, indicates that

      i. Nature also removes CO_2 quite rapidly and

      ii. if we replicate this form of OIF, we may be able to achieve 60 Gt/yr CO_2 removal.

4) Develop fast, redundant and reliable measurement systems

   Current oceanographic protocols measure particulate and dissolved carbon through the water column down to the seafloor. These measurements may be too slow, expensive, difficult to verify, and susceptible to variations in ocean currents and chemistry to be used to optimize a process.

   With a climate goal to reduce atmospheric CO_2, reliable data can be obtained from atmospheric CO_2 sensors on satellites and marine buoys. They provide rapid, verifiable feedback to optimize and scale up the CO_2 removal process. This type of measurement and verification can:

   a) Measure short-term CO_2 removal from a (buoy-based) CO_2 sensor array, verified by satellite data.

   b) Separately measure long-term CO_2 re-release after iron fertilization using the NASA OCO-2 and OCO-3 satellite platforms. [18] These satellites can monitor the whole ocean. The data is readily available and baseline data is available back to 2014.

   c) Enable multiple simultaneous short-term CO_2 removal optimization tests with a low-cost sensor array.

5) Implement and optimize the CO_2 removal process

a) Implementation in this case will be based on the natural processes of OIF that occur before ice ages and following some volcanoes, i.e. Mt. Pinatubo. In this eruption, ash fell into a large, down-welling eddy. This type of converging eddy appears to account for the magnitude of CO_2 removal, as 1) the semi-bounded nature of an eddy keeps the concentration of iron and nitrates sufficiently high for the growth of phytoplankton, and 2) the downwelling attribute accelerates the sinking of biocarbon before it is fully eaten and metabolized by zooplankton and fish.

b) Therefore, implementing OIF in areas down-welling/converging ocean eddies will be intended to maintain sufficient concentration of iron and accelerate the sinking of carbon.

c) It is important to optimize the iron formula and its application to accelerate nitrogen-fixing bacteria as well as phytoplankton.

D. Alternatives

Various methods have been proposed for reducing CO_2 in the atmosphere. These include Direct Air Capture, Ocean Alkalinity Enhancement, Enhanced Rock Weathering, and Biomass Carbon Removal and Storage.

Various projects are underway to evaluate such methods. It will be important to assess the ability for each method to scale up to contribute to efforts to restore CO_2 in the atmosphere to pre-industrial levels at costs that are practical. These evaluations are beyond the scope of this paper.

III. Future Work

A. Field work is needed to validate these concepts

A pilot study is needed to confirm (a) the effectiveness of using OIF to stimulate natural processes to remove the needed amounts of CO_2 from the atmosphere and (b) to collect data to help refine the methods for scaling up the process.

In particular, a pilot study is envisioned to test these hypotheses:

1) sufficient levels of iron serve to stimulate nitrate production, thus extending a phytoplankton bloom, and

2) downwelling accelerates long-term CO_2 removal.

These hypotheses can be tested and rapidly refined by replicating and modifying the protocol used in the 2012 Haida OIF experiment in the Gulf of Alaska. [19]

There are two main principles to follow in such a pilot study. First, apply iron in a way designed to replicate what occurred in nature in the past. Second, tailor measurement, reporting, and verification technology to collect the data needed for measuring effectiveness and refining the methodology.

The Haida test distributed roughly 100 tons of iron sulfate and a smaller amount of iron oxide from a ship to a 100 km x 100 km region inside an *upwelling* eddy. The expedition produced a significant phytoplankton bloom, followed by a historically large pink salmon catch the following year—presumably since their food supply multiplied, as phytoplankton form the base of the marine food web. However, today a test designed to optimize and scale up OIF for CO_2 removal would use multiple test quadrants, real time CO_2 measurement, and repeated nutrient application in a *downwelling* eddy.

B. Methodology

The authors suggest replicating the CO_2 removal results of the Pinatubo CO_2 pause starting with the methodology of the 2012 experiment. The proposed approach will utilize less than 3 percent of the area affected by the eruption in 1991 and employ a downwelling eddy and sufficient iron for cyanobacteria growth. (Fig. 5) Multiple simultaneous tests will be conducted to determine the conditions that maximize CO_2 removal.

A 100 km x 100 km area at the center of a downwelling eddy will be subdivided into 16 test quadrants. (Fig. 6) Twenty-five CO_2 sensor buoys positioned around each quadrant's perimeter will measure atmospheric CO_2 changes. Each quadrant will be supplemented with different nutrient formulations, which will be optimized and replenished roughly on a monthly basis. An uncrewed solar powered ship will traverse the quadrants every 4-7 days to monitor several parameters, including Trichodesmium activity.

The uncrewed vessel will be equipped with colorimetric sensors to measure chlorophyll and cyanobacteria, nitrate sensors, and acoustic sensors to detect fish biomass.

As noted above, nitrogen fixation in Trichodesmium is expected to require 20 times the iron concentration required for phytoplankton. This will be determined by testing at various concentrations in test quadrants.

Each distribution of iron in the 10,000 km^2 project area will disperse about 100 tons (roughly 100 cubic meters) total of iron sulfate, iron oxide, and a proprietary product from a ship roughly 30 m long. This works out to about 0.01 gram per square meter. The distribution interval will be adjusted based on data from the buoys and uncrewed vessel.

Several formulations will be tested in the various test sections, based on unpublished results from the 2012 test. That test showed that fine commercial iron oxide and iron sulfate commercial fertilizer had similar effectiveness per ton. However, they resulted in different phytoplankton species ratios.

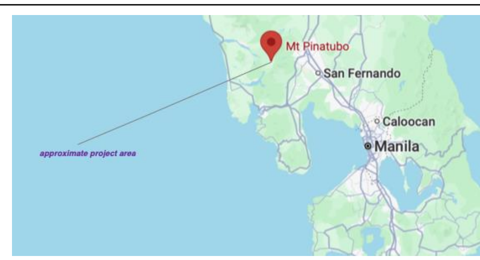

Fig. 5. Approximate project area.

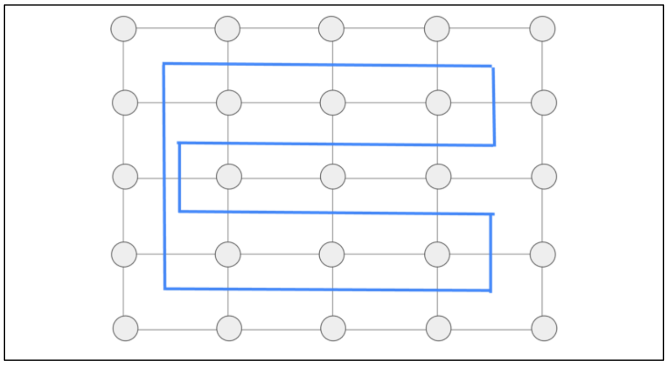

Figure 6. Buoy locations and uncrewed vehicle path

A proprietary buoyant iron sulfate formulation embedded in cellulose was developed after the 2012 test. That formulation will also be tested at a range of concentrations.

C. Measurement, Reporting, and Verification

The CO_2 removal rate in each test quadrant will be measured by subtracting CO_2 measurements between buoys upwind and downwind of the OIF test area. pH and CO_2 sensors will be calibrated and tested before and after the test, but not during the test, since the buoys will be operating unattended.

In addition, an uncrewed vessel will continuously traverse the OIF area, measuring levels of nitrate, chlorophyll, cyanobacteria, and fish biomass.

In the pilot area, we expect approximately 15 ppm/hr carbon dioxide reduction, based on data from earlier tests.

Where

- CO_2u is CO_2 ppm upwind
- CO_2d is CO_2 ppm downwind
- WS is wind speed (km/hr)
- BS is Buoy Spacing (km)
- Atm pressure (tons/km^2)
- OIF area is 10,000 km^2
- Atmospheric pressure is 14.7 lb/in^2 or 10,335,123 tons/km^2

$$CO_2 \text{ rate (ppm/hr)} = (CO_2d - CO_2u) * \text{WS (km/hr)} / \text{BS (km)} \quad (1)$$

$$CO_2 \text{ rate (tons/hr)} = CO_2 \text{ (ppm/hr)} * 0.000001 \text{ (ton/g)} * 10{,}000 \text{ (km}^2) * 10{,}335{,}123 \text{ (tons/km}^2) \quad (2)$$

Say (CO_2d - CO_2u) is 15 ppm, WS is 10 (km/hr), and BS is 25(km)

$$CO_2 \text{ rate (ppm/hr)} = 15 \text{ (ppm)} * 10 \text{ (km/hr)} / 25 \text{ (km)} = 6 \text{ (ppm/hr)} \quad (3)$$

$$CO_2 \text{ rate (ton/hr)} = 6 \text{ (ppm/hr)} * 0.000001 \text{ (ton/g)} * 10{,}000 \text{ (km}^2) * 10{,}335{,}123 \text{ (tons/km}^2) = 620{,}107 \text{ (ton/hr)} \quad (4)$$

After one year:

$$620{,}107 \text{ (ton/hr)} * 8760 \text{ (hr/yr)} = 5{,}431{,}140{,}649 \text{ (ton/yr)} \quad (5)$$

or about 5.4 Gt/yr in the project area.

Of course, this is an oversimplification, since wind, plankton photosynthesis, and air/sea exchange are probably not uniform. However, integrating results over the project area and over time should yield a good idea of what is occurring.

The downwelling hypothesis will be tested by repeating the optimized test conditions in nearby non-eddy and upwelling eddy regions.

NASA Orbiting Carbon Observatory-2 (OCO-2) data will be used to monitor whether CO_2 is being re-emitted back into the atmosphere in the project area. [18] (Fig. 7) The rate of CO_2 emission is calculated by comparing CO_2 levels upwind and downwind in the OCO-2 data. OCO-2 returns the wind vector with each CO_2 measurement. Because CO_2 can only be emitted or removed at the ocean surface, the calculated emission rate corresponds to the ocean surface.

The pilot is expected to remove between 1 and 100 Mt CO2 over 3 months. This rate is thousands of times higher than existing CO_2 removal methods, so accuracy of plus or minus 20 percent will not affect conclusions.

D. Risk Mitigation

Various authors have conjectured that OIF might cause adverse environmental impacts in the ocean. However, these assertions are only theoretical and, in particular, there have been no evaluations of the specific approach being considered here. No lasting adverse effects in the ocean are reported to have resulted from the Mt. Pinatubo eruption. The observed atmospheric effects of the Mt. Pinatubo eruption dissipated in under two years and other instances of OIF activity have been associated with beneficial increases in fishery production.

The data collection planned for the proposed pilot study will be invaluable for evaluating potential impacts to the environment from OIF. The proposed pilot study is in a limited area and of limited duration. Consequently, effects on the environment are expected to be observable, but not of significant magnitude.

Measurements of chlorophyll, cyanobacteria, nitrate, and fish biomass will provide indicators to help assess impacts during the pilot study.

E. Regulatory Requirements and Stakeholder Engagement

The regulatory situation for marine carbon dioxide removal in the open ocean is still evolving and data from the proposed pilot project can be used to help inform these discussions.

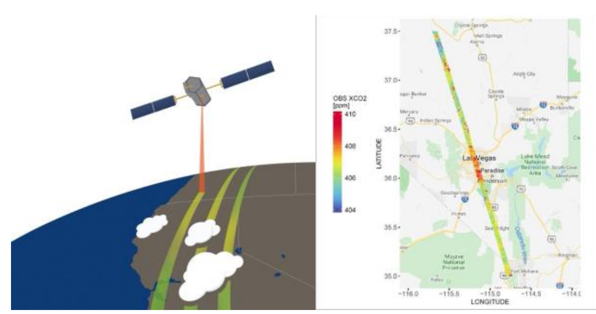

Fig. 7. OCO-2 satellite monitoring. [18]

Since the most likely area for the pilot project is within or near The Philippines Economic Exclusion Zone in the SouthChina Sea, it appears likely there will need to be an Environmental Impact Statement under the Philippine Environmental Impact Statement System and an associated Environmental Compliance Certificate.

While the International Maritime Organization has discussed an Ocean Fertilization Assessment Framework for proposed research, it is not yet in force. [20] [21] If it were in force, the proposed pilot project would qualify as scientific research.

F. Scaling

Traditionally, scientific measurements constitute the majority of the mission cost. By using automated buoy and satellite CO_2 data collection, the measurement cost can be radically reduced. Within a few years even the iron distribution can be done from uncrewed vessels. At scale, this leads to overall costs well below $1 per ton of CO_2 removed. In 2022, the National Academies of Sciences, Engineering, and Medicine published a study finding it is possible to remove a ton of CO_2 for less than 40 cents. [22]

While scaling up to the level needed to restore the atmosphere is beyond the scope of the proposed pilot study, a rough estimate of the global atmospheric CO_2 removal potential using OIF can be made. Several factors go into such an estimate, including:

- the aggregate area of iron dust distribution summed from various project locations in the ocean around the globe
- the average amount of CO_2 removed during a year of iron dust distribution during conditions that vary seasonally
- an average rate at which CO_2 will be captured by photosynthesis, given that a higher gradient from the atmosphere to the ocean will exist at the start of full-scale operations and likely taper off as the concentration in the atmosphere decreases

The observed effects associated with the Mt. Pinatubo volcano eruption provide a starting point. As noted above, a long-term removal of 20 Gt CO_2 was observed in the year of 1992 as the result of an estimated 5 Gt of ash being deposited into the ocean downwind from the eruption.

We need to remove over 1,000 Gt CO_2 over 20 years to restore CO_2 to historically safe levels by 2050. As noted above, we estimate that a rate of 60 Gt/yr will be needed.

Observed natural OIF has been observed to remove 20 g C/m^2/day. [23] This means 2.2 million km^2 of ocean out of the 360 million km^2 ocean area is sufficient to remove the needed CO_2 (calculation below). That is, 0.6% of total ocean area is required. If each eddy is 70,000 km^2 (roughly 300 km diameter), this requires 31 eddies.

The molecular weight (mw) of carbon is 12 and of CO_2 is 44,

$$44 / 12 = 3.66 \quad (6)$$

$$20 \text{ (g C/m}^2\text{/day)} * 3.66 \text{ (mol wt CO}_2\text{/mol wt C)} = 73.2 \text{ (g CO}_2\text{/m}^2\text{/day)} \quad (7)$$

$$73.2 \text{ (g CO}_2\text{/m}^2\text{/day)} * 365 \text{ (days/yr)} * 10^{-6} \text{ (ton/g)} * 10^{6} \text{ (m}^2\text{/km}^2\text{)} = 26{,}718 \text{ (tons CO}_2\text{/km}^2\text{/yr)} \quad (8)$$

or 0.000027 (Gt CO_2/km^2/yr)

Given that we estimate 60 Gt/yr needs to be removed,

$$60 \text{ (Gt CO}_2\text{/yr)} / 0.000027 \text{ (Gt CO}_2\text{/km}^2\text{/yr)} = 2.2 \text{ million km}^2 \quad (9)$$

Earth's oceans cover 360 million km^2

$$2.2 \text{ million km}^2 / 360 \text{ million km}^2 = 0.006 \text{ of ocean area} \quad (10)$$

or 0.6% of ocean area.

More refined calculations will become possible with data from the proposed study.

IV. Conclusion

We understand what is needed to restore the atmosphere and how replicating natural processes offers a way to accomplish what is needed. To validate the proposed approach, a pilot study needs to be done with appropriate instrumentation. Then, if the hypothesis is confirmed, efforts can be undertaken to scale up the technology. Once the pilot study has been conducted, data will be available to conduct a cost-benefit analysis for scaling up OIF. Modeling indicates that replication in 31 downwelling eddies 300 km in diameter will be sufficient.

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