Large-Scale, Long-term CO_2 Storage by Ocean Iron Fertilization

George J Hirasaki

September 23, 2025

3rd International Whole Value Chain CCUS Conference Week

The New York Times

OPINION

GUEST ESSAY

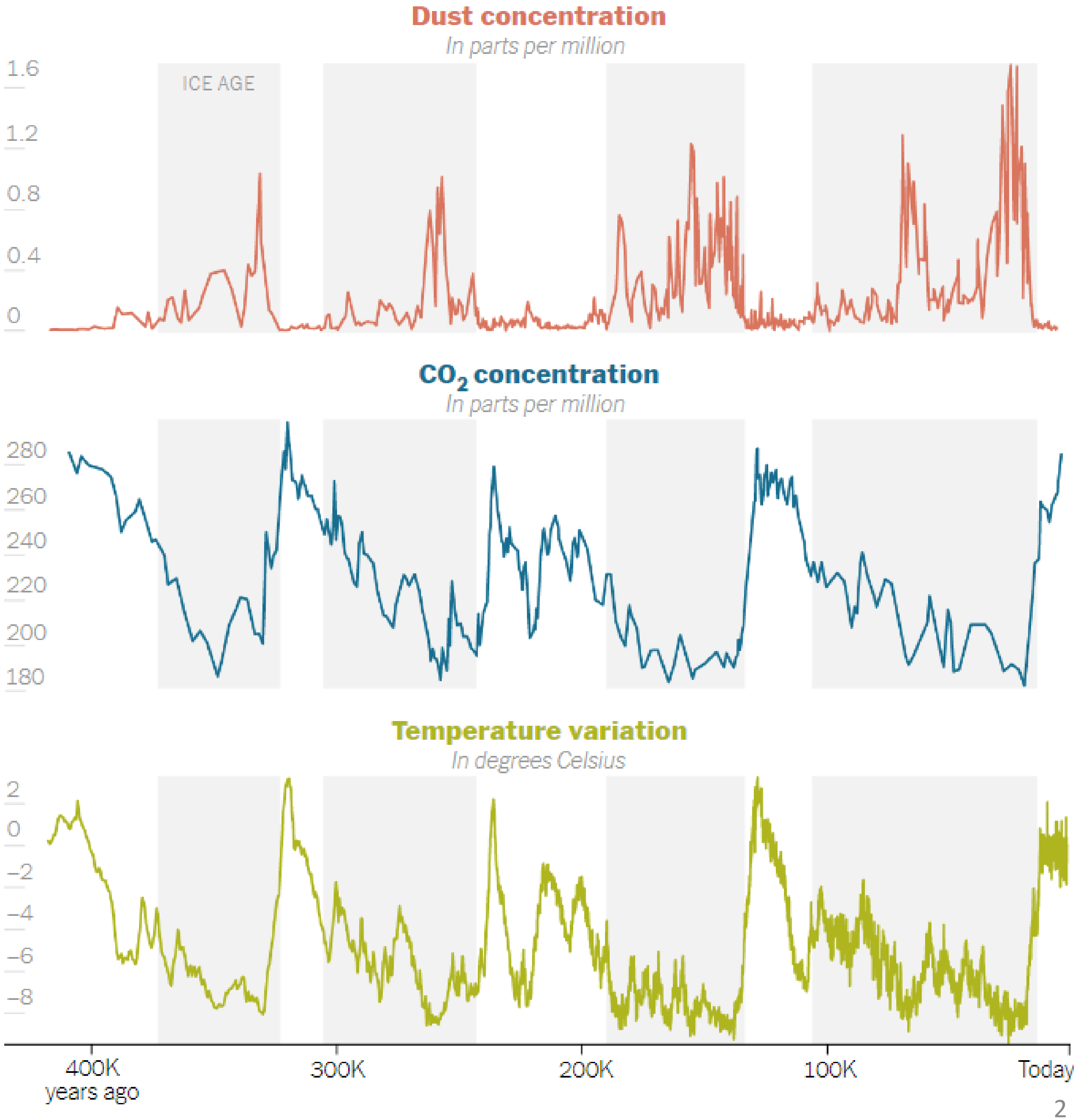
Iron Dust Could Reverse the Course of Climate Change

Sept. 14, 2023

By John T. Preston, Dennis Bushnell and Anthony Michaels

…atmospheric dust Fe supplies were 50 times higher during the last glacial maximum(LGM). Because of this Fe enrichment, phytoplankton growth may have been greatly enhanced … may have contributed to the LGM drawdown of atmospheric CO2 to levels of less than 200 ppm.

Martin, 1990.



A Research Strategy for **Ocean-based Carbon Dioxide Removal** and Sequestration

Committee on A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration

(2022)

Ocean Studies Board

Division on Earth and Life Studies

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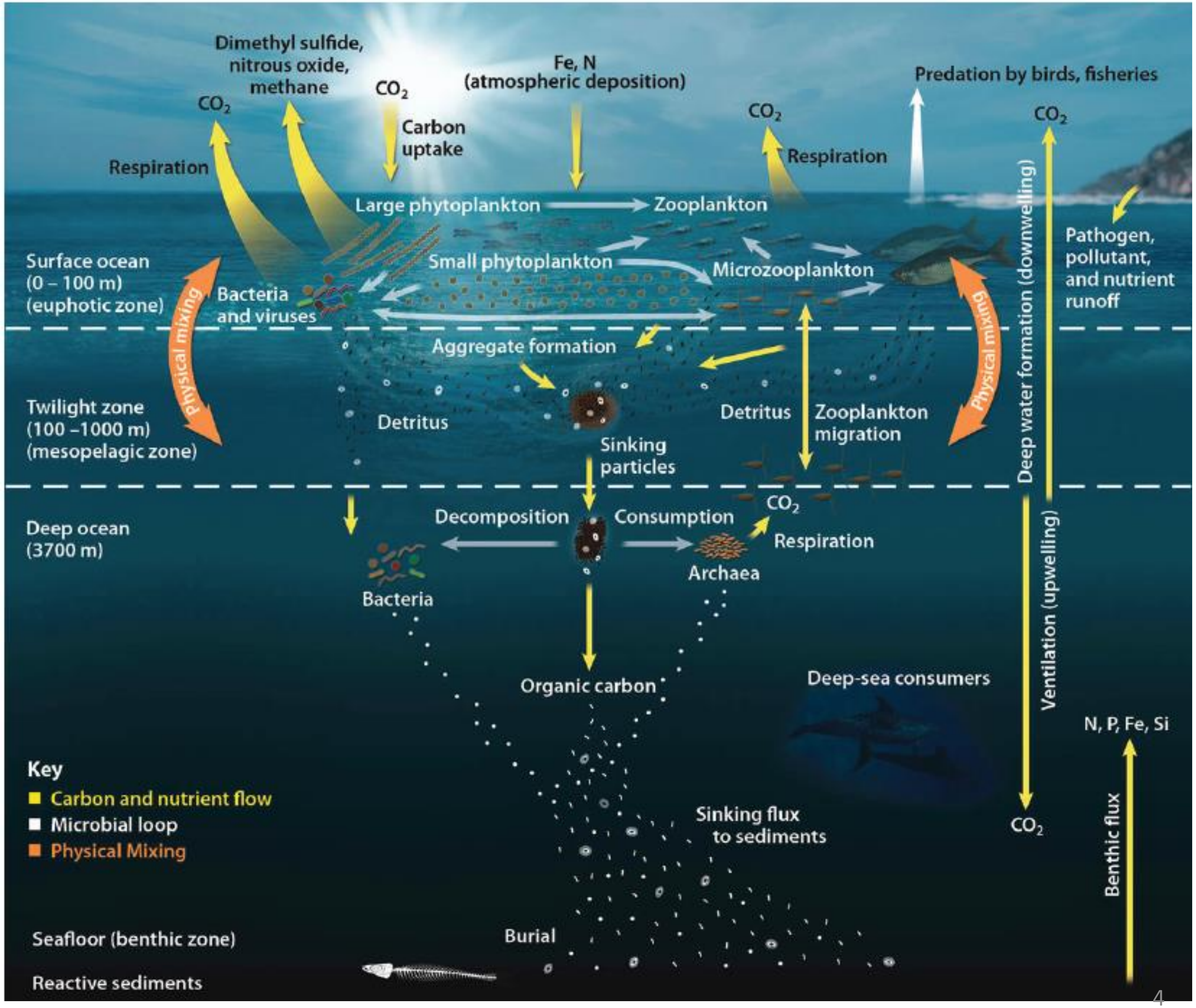
Schematic of the ocean carbon cycle illustrating carbon and nutrient flows (yellow), food web and microbial loop processes (white/light blue), and physical mixing (orange).



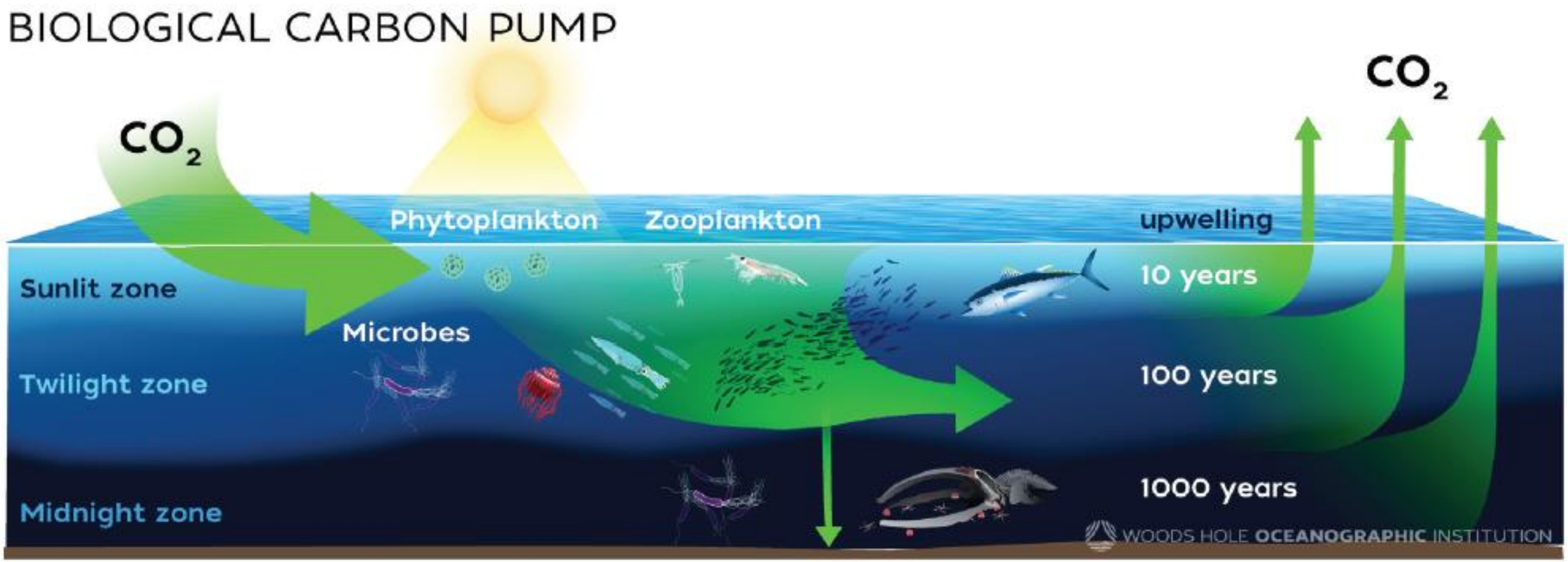


FIGURE 3.1 Schematic of the ocean BCP with an emphasis on C transport to depth and return times relevant to the timescale of C storage in the mid and deep ocean. SOURCE: Natalie Renier, Woods Hole Oceanographic Institution.

Surface mixed-layer nitrate concentration, micromole/liter

white crosses – artificial ocean iron fertilization (aOIF)

red crosses – natural OIF

green cross - Fe and P enrichment

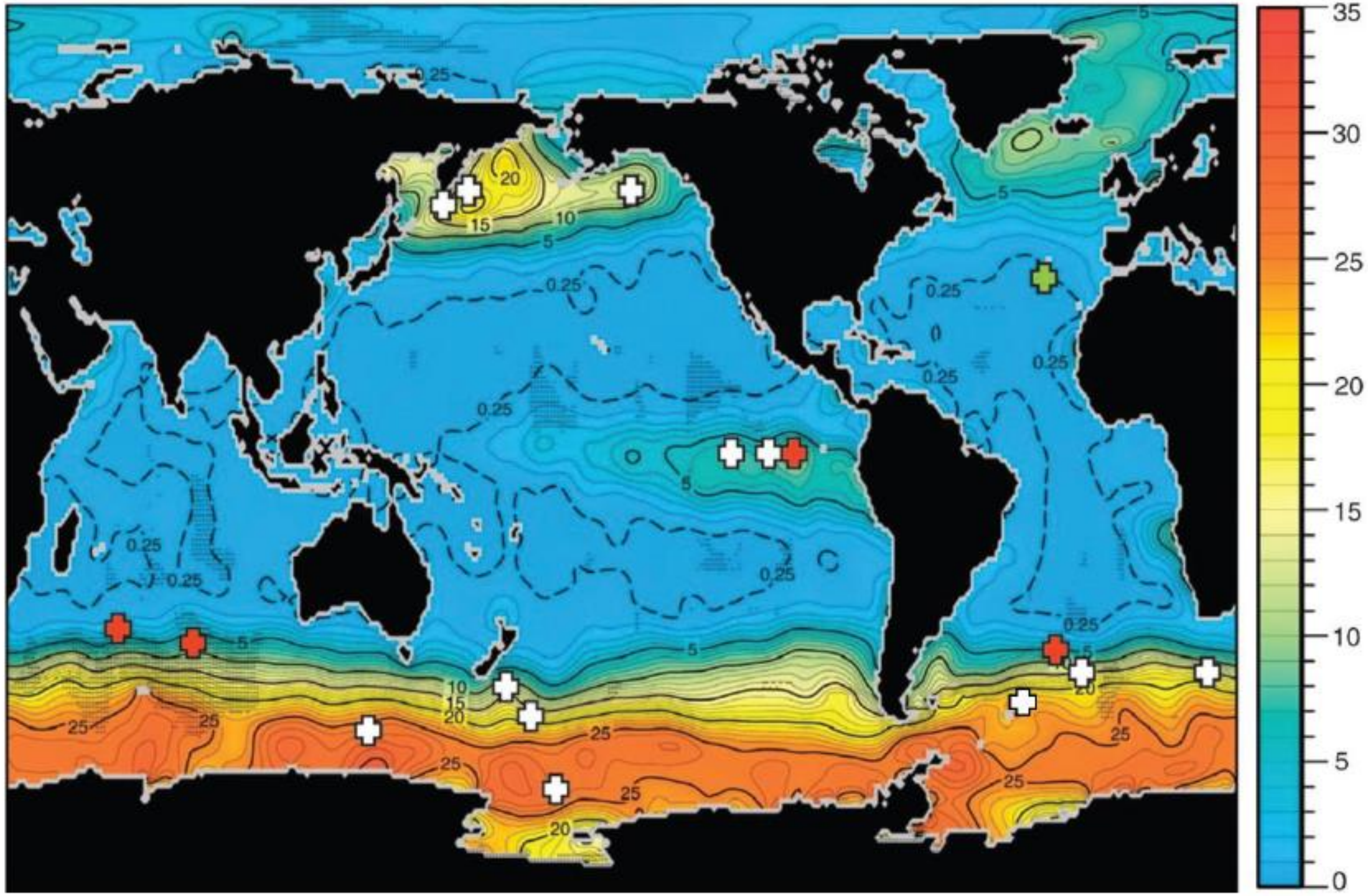


FIGURE 3.2 Annual surface mixed-layer nitrate concentrations in units of micromoles per liter with approximate site locations for artificial ocean iron fertilization (aOIF) experiments (white crosses), natural OIF studies (red crosses), and a study of Fe and P enrichment (green cross). SOURCE: Modified from Boyd et al., 2007, with addition of LOHAFEX aOIF site study in 2009 (Smetacek and Naqvi, 2010).

Fraction of CO_2 retention for 100 years or more that leaves the surface euphotic zone

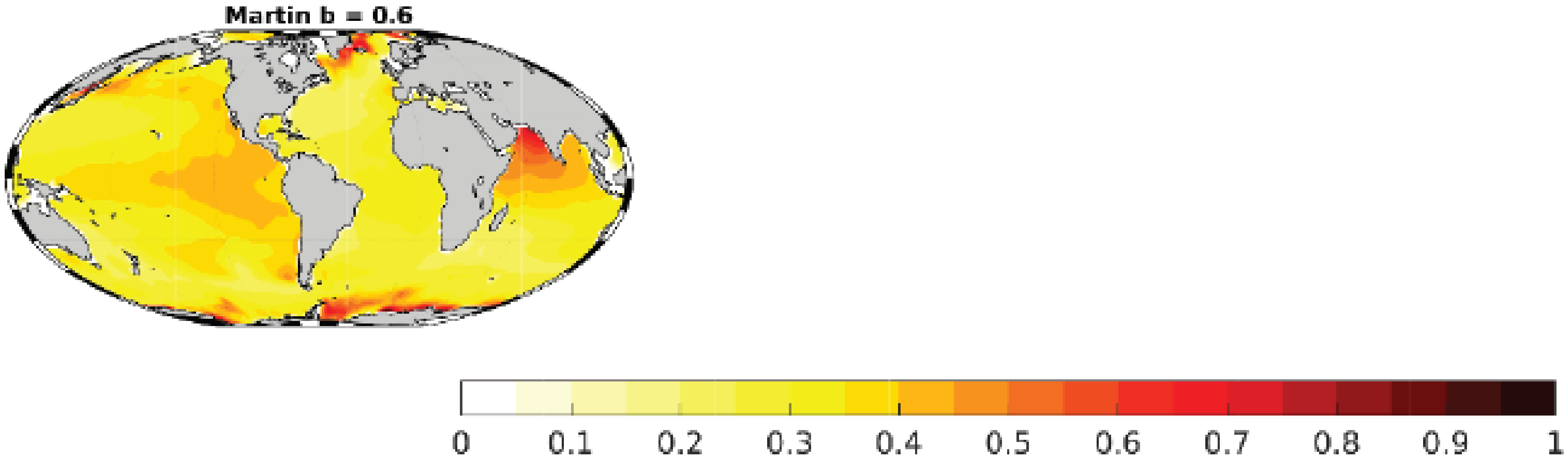


FIGURE 3.3 Color shows the fraction of CO_2 retention for 100 years or more, in response to a surface bloom. Values for *b* follow the parameterization by Martin et al. (1987) with 0.8 being a global average, and 1.0 and 0.6 indicating greater and lower particulate organic carbon flux attenuation, respectively. SOURCE: Adapted from Figure S3 in Siegel et al., 2021a, licensed by Creative Commons CC BY 4.0.

b is a best-fit parameter for POC flux versus depth between generally 100 and 1,000 meters.

Why ocean iron fertilization?

- **Photosynthesis depends on chlorophyll**
- **Iron is an essential element in the production of chlorophyll**
- **Iron is abundant in the earth crust but has extremely low solubility in oxygenated water**
- **Nature adds iron to the oceans from (1) rivers*, (2) windblown dust, and (3) volcanic ash**
- **Iron can be added to the ocean as iron (II) sulfate or ferrous sulfate, diluted to nano-molar concentrations with the propeller wash of the ship**
- **This should <u>only</u> be done in parts of the oceans where there will be no harmful effects due to additional photosynthesis**

Moore, J. K. and S. C. Doney (2007), Iron availability limits the ocean nitrogen inventory stabilizing feedbacks between marine denitrification and nitrogen fixation, Global Biogeochem. Cycles, 21, GB2001, doi:10.1029/2006GB002762.

Grider, R.J. and La Roche, J., The role of iron in phytoplankton photosynthesis, and the potential for iron-limitation of primary productivity in the sea, *Photosynthesis Research* 39: 275-301, 1994.

* Columbia River now has 60 dams in its watershed.

Cost of carbon sequestration by OIF

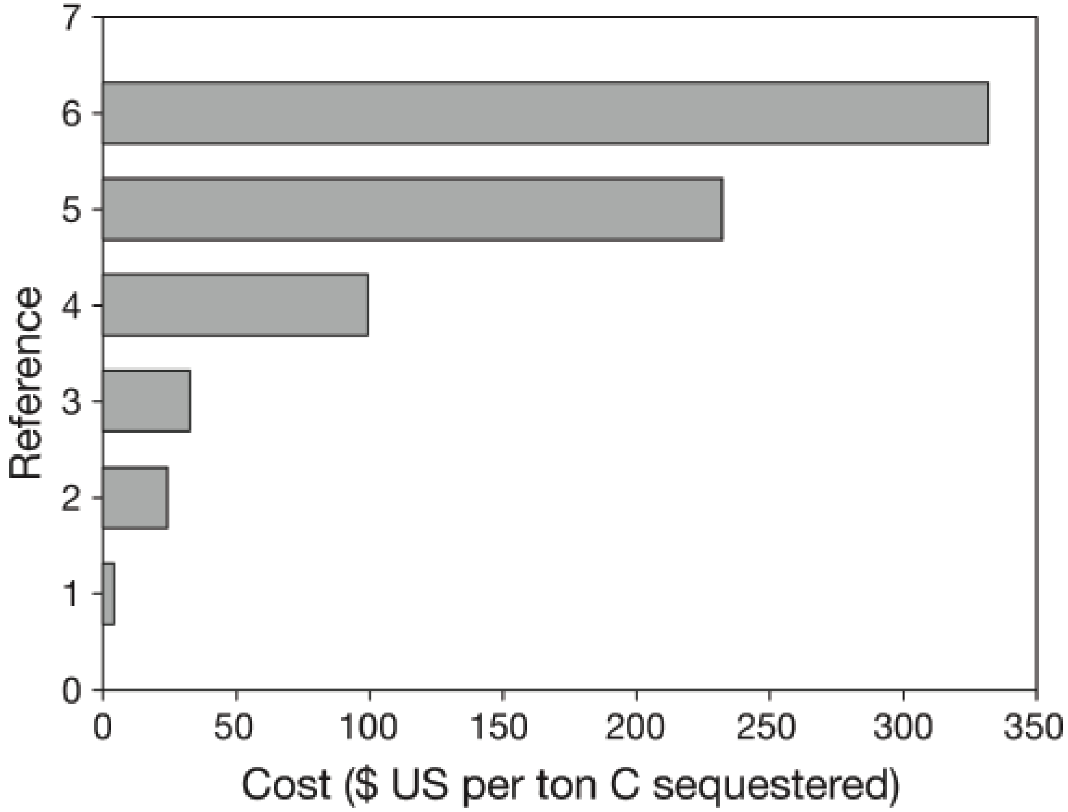


FIGURE 3.5 Estimates of the cost of C sequestration by OIF. These six estimates differ largely because of varying ratios of Fe:C sequestered as detailed in the original references and discussed above in Export Efficiencies. Note that costs based on CO_2 sequestration would be 3.7 times lower. SOURCE: Boyd, 2008.

The high range in costs is because we don't know those C export efficiencies to the deep sea, but in any scenario, costs will be low and lower than other CDR approaches, i.e. no infrastructure, energy from sun, a little Fe goes a long way with Fe:C ratios of 1:100,000 in nature and 1:1000 in past field studies (where we lost >90% of the Fe due to precipitation, so not bioavailable. I'd like to think we can get to 1:10,000 in next expts. (Buesseler, 2023)

Summary of Ocean CDR Scale-Up Potential

Knowledge base: Medium–High

Considerable experience relative to any other ocean CDR approach with strong science on phytoplankton growth in response to iron, less experience on fate of carbon and unintended consequences.

Natural iron-rich analogs provide valuable insight on larger temporal and spatial scales.

Summary of Ocean CDR Scale-Up Potential

Efficacy: Medium–High Confidence

Biological carbon pump known to work and productivity enhancement evident.

Natural systems have higher rates of carbon sequestration in response to iron but low efficiencies seen thus far would limit effectiveness for CO_2 removal

Summary of Ocean CDR Scale-Up Potential

Durability: Medium

10–100 years
Depends highly on location and biological carbon pump efficiencies, with some fraction of carbon flux recycled faster or at shallower ocean depths;

however, some carbon will reach the deep ocean with >100-year horizons for return of excess CO_2 to surface ocean

Summary of Ocean CDR Scale-Up Potential

Scalability: Medium–High

Scale could be higher than 1 Gt CO2/yr if we include low nutrient areas where Fe should stimulate N2 fixers (using up excess P) (Buesseler, 2023)

(medium-high confidence)
Potential C removal >0.1–1.0 Gt CO_2/yr

(medium confidence)
Large areas of ocean have high-nutrient, low-chlorophyll conditions suitable to sequester >1 Gt CO_2/yr.
Co-limitation of macronutrients and ecological impacts at large scales are likely.
Low-nutrient, low-chlorophyll areas have not been explored to increase areas of possible deployment.

(Medium confidence): based on 13 field experiments)

Summary of Ocean CDR Scale-Up Potential

Environmental risk: Medium

Risk- risk of field experiments (longer/larger) is near zero in terms of causing permanent damage of regional shifts in ecosystems, deep ocean properties. Risks of large scale Gt deployments is tbd and requires better models and new field data

(Buesseler, 2023)

(low–medium confidence)
Intended environmental impacts increase net primary productivity and carbon sequestration due to changes in surface ocean biology.

If effective, there are deep-ocean impacts and concern for undesirable geochemical and ecological consequences.

Impacts at scale: uncertain

Governance

- … in 2008, the parties to the London Convention and Protocol adopted a nonbinding resolution stating that nutrient fertilization projects "should not be allowed," unless they are undertaken for the purposes of "legitimate scientific research" (Art. 3-5, Resolution LC-LP.1, 2008).
- In 2013, the parties to the London Protocol agreed to an amendment that effectively prohibits nutrient fertilization, except for research purposes (Resolution LP.4(8), 2013).
- Notably, the amendment would not bind the United States, which is only a party to the London Convention and not the London Protocol.

Science needs to lead the way

Download at oceaniron.org

EXPLORING Ocean Iron Solutions

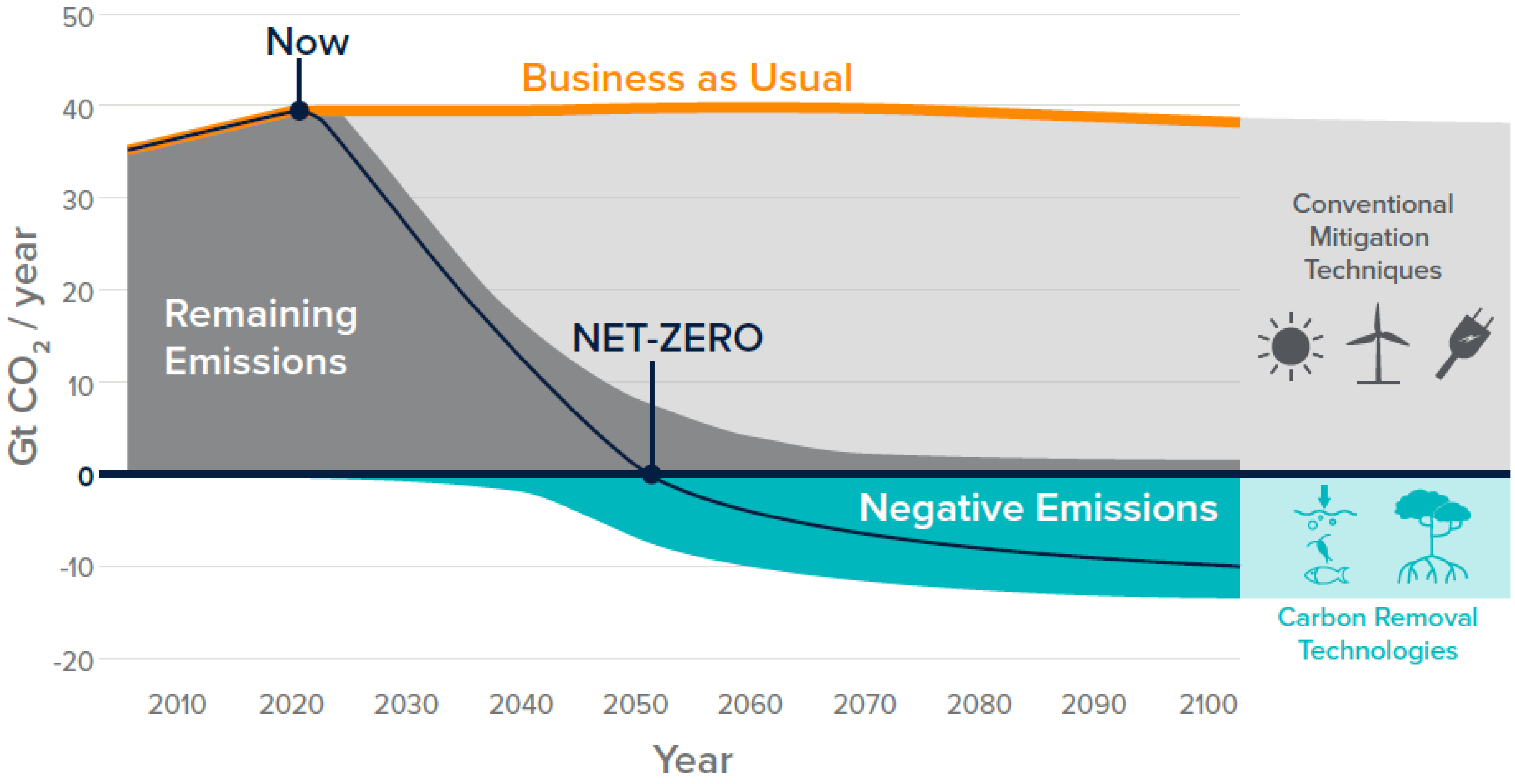
International group dedicated to assessments of ocean iron fertilization for CDR

- ✓ durability
- ✓ scaling
- ✓ ecological impacts
- ✓ costs
- ✓ ethical standards

First Forum- March 2022
White paper- Nov. 2022
“Path Forward” doc- summer 2023

Projected CO_2 emissions and combined reductions in emissions and CDR needed to keep warming below 1.5° C targets.

Adapted World Resources Institute from IPCC reports.



Guiding Principles
For ocean carbon dioxide removal studies

1. Prioritize collective benefit for humans and the environment
2. Establish clear lines of responsibility to oversee studies
3. Commit to open and cooperative research, including risk assessments
4. Perform evaluation and assessment in an iterative and independent manner
5. Engage the public in consideration of climate intervention options

Buesseler, Ramakrishna, Leinen
Nature Correspondence, June 30, 2022