Iron Fertilization:

A Part of the Solution or a Part of the Problem?

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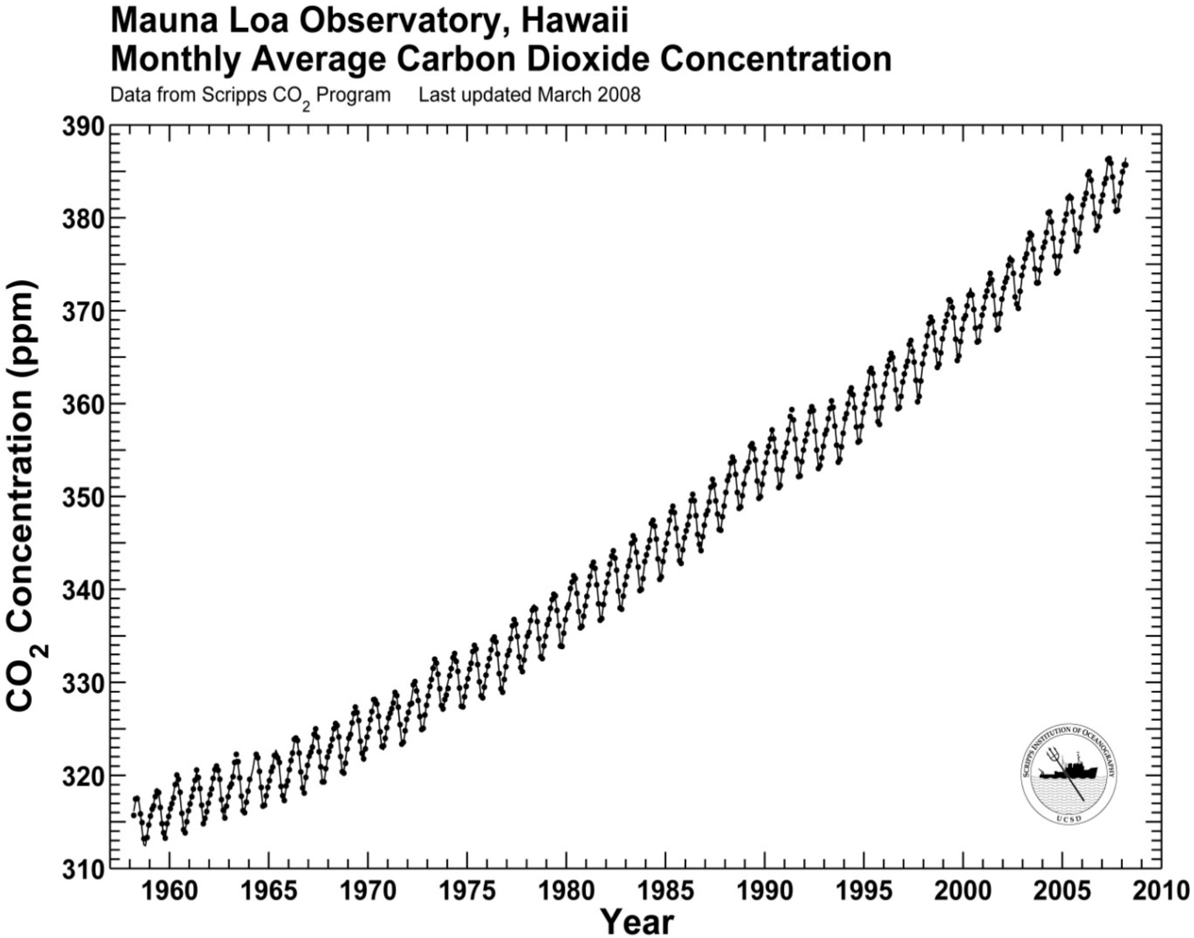
Climate Change/Photosynthesis

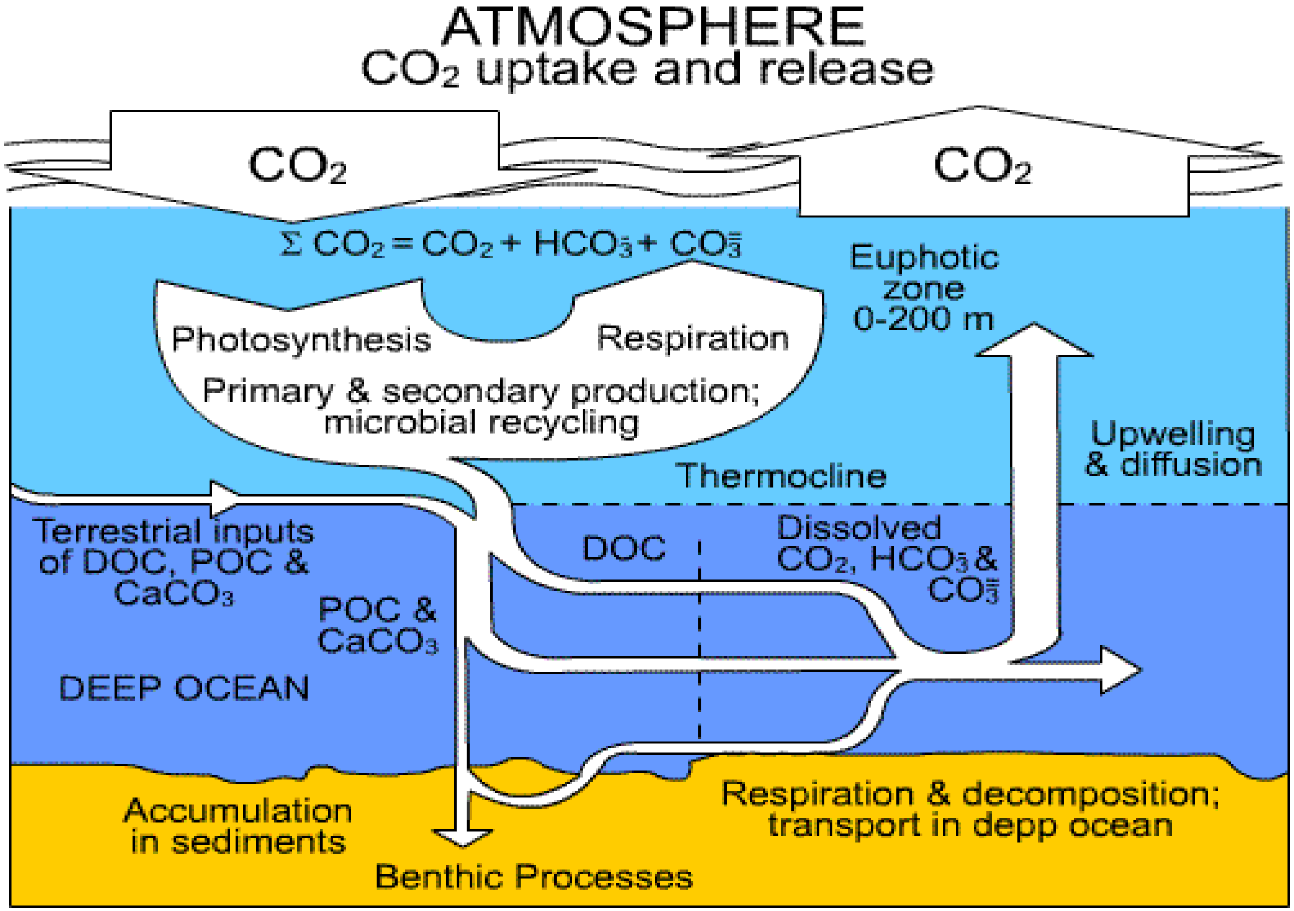


- CO_2 is rising
- Photosynthesis has an effect on atmospheric CO_2
- Oceanic algae are estimated to be 1% of plant biomass but fix 50% of CO_2 .

The Keeling Curve

Carbon Pump

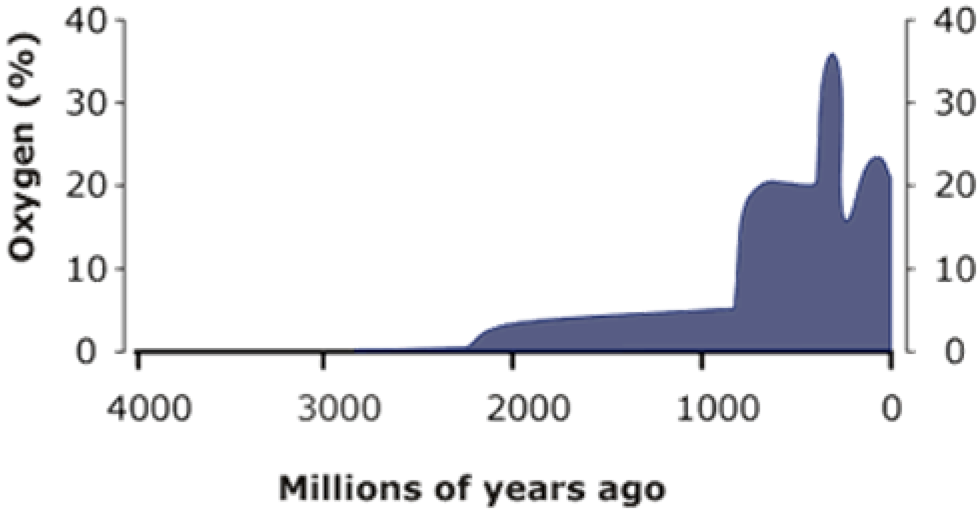
- Approximately 90Gt per year flux of CO_2 between ocean and atmosphere
- Plant growth is usually limited by nitrogen an phosphorus
- Iron is a key micronutrient in living organisms, especially phytoplankton.



Source: British Government Panel on Sustainable development
http://www.sd-commission.org.uk/panel-sd/position/co2/annb.htm, accessed 4/15/08

Iron Limitation: *Phytoplankton Evolution*

(Phytoplankton did it to themselves)



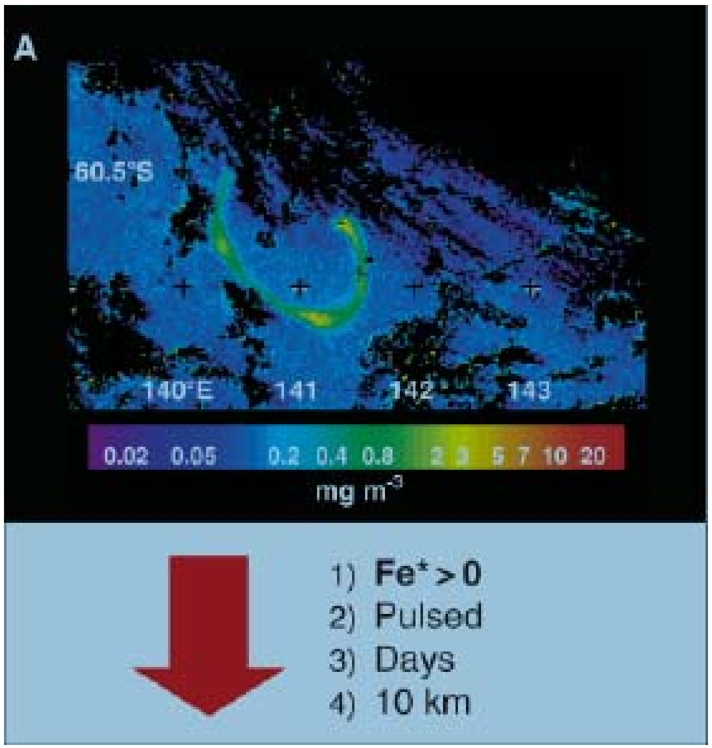
- Photosynthetic phytoplankton evolve during period of high oceanic dissolved Fe content

↑ Photosynthesis = ↑ **O_2** = Oxidation and precipitation Fe

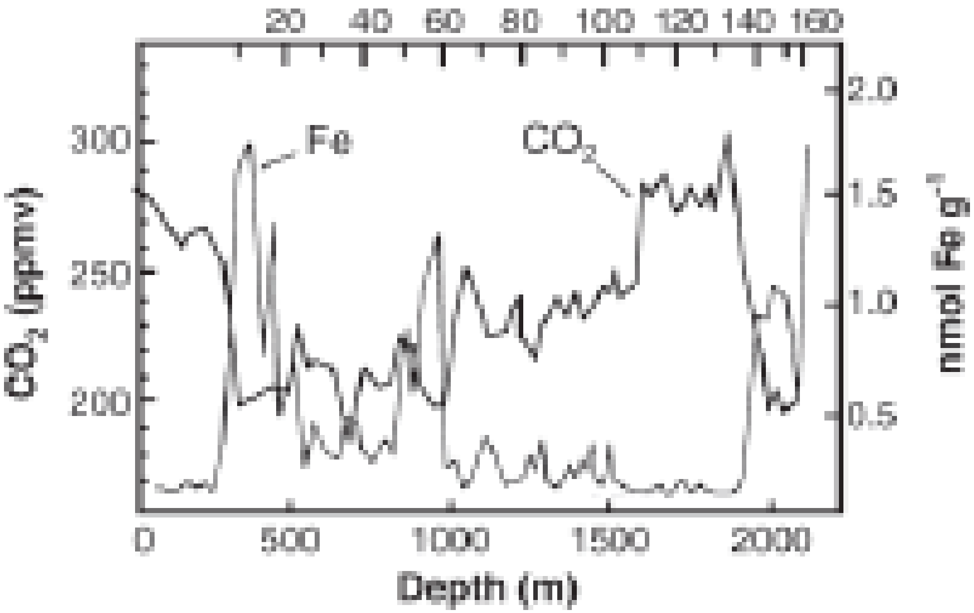
http://www.rsbs.anu.edu.au/O2/O2_2_Abundence.htm

The Geologic Precedent

- 30% of the CO_2 drawdown in glacial periods is attributed to increased productivity induced by Fe-rich dust



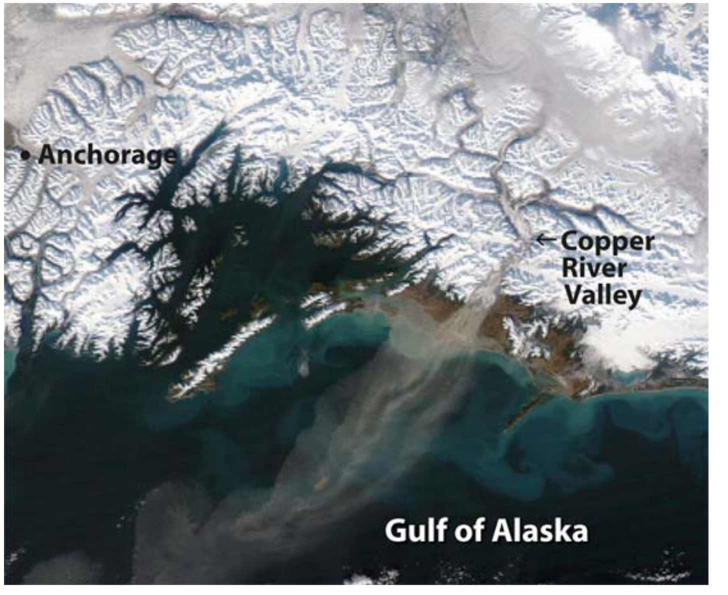
Boyd et al., 2007



Boyd et al., 2007

Martin's Iron Hypothesis

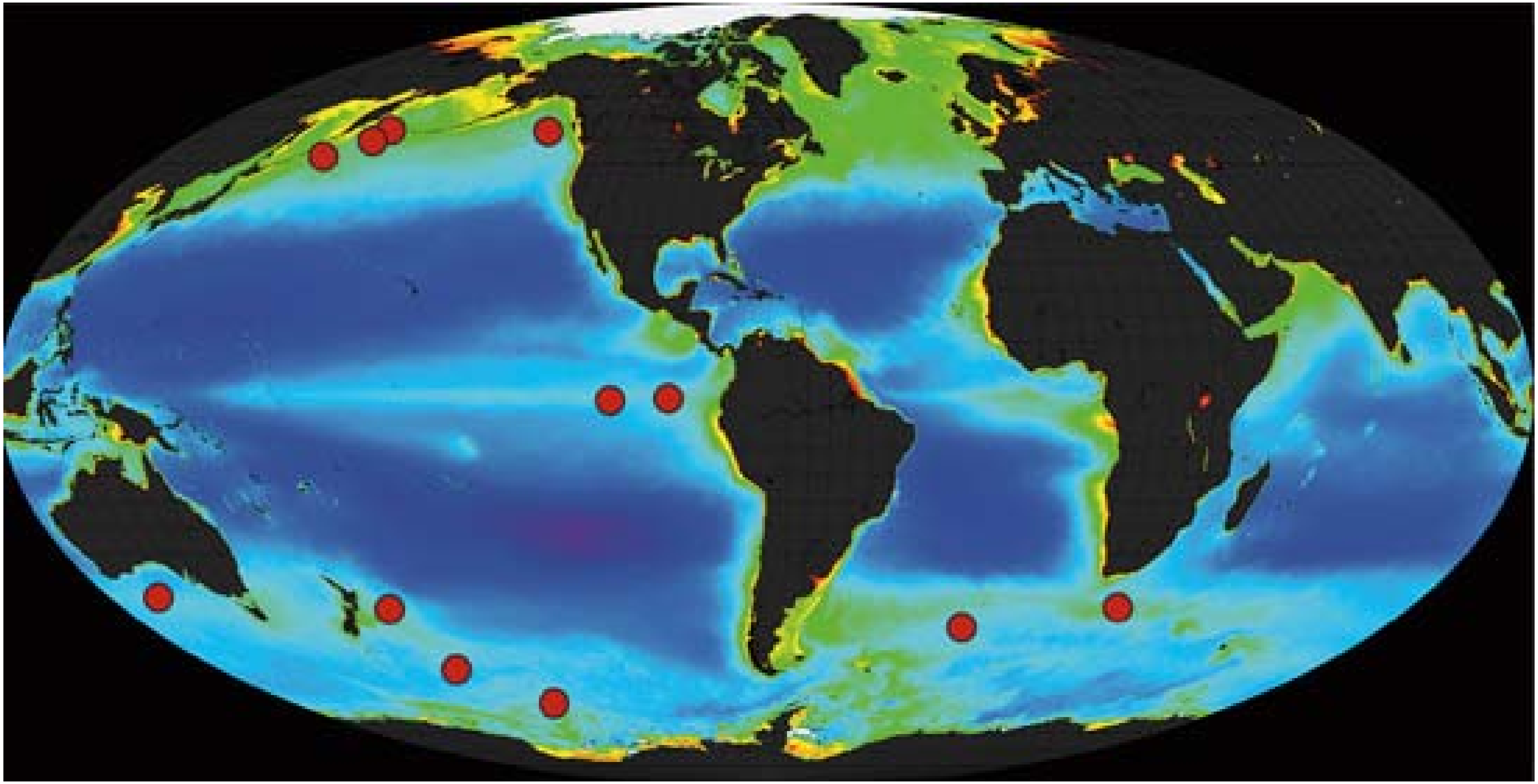
- How to explain ice ages?
- The pump isn't running at full capacity - HNLC
- On geological time, Fe inputs were higher during glacial maxima
- Can we understand this important earth system?
- 12 research expeditions later: Small scale Fe fertilization can cause small scale blooms



Dust plume from Alaska glacial sediments

Source: http://www.whoi.edu/oceanus/viewImage.do?id=57456&aid=34167

Previous Experiments



Implications of Martin's work

↑ Fe in HNLC

↓

↑ Photosynthesis

↓

↑ Phytoplankton

↓

↑ CO_2 drawdown

↓

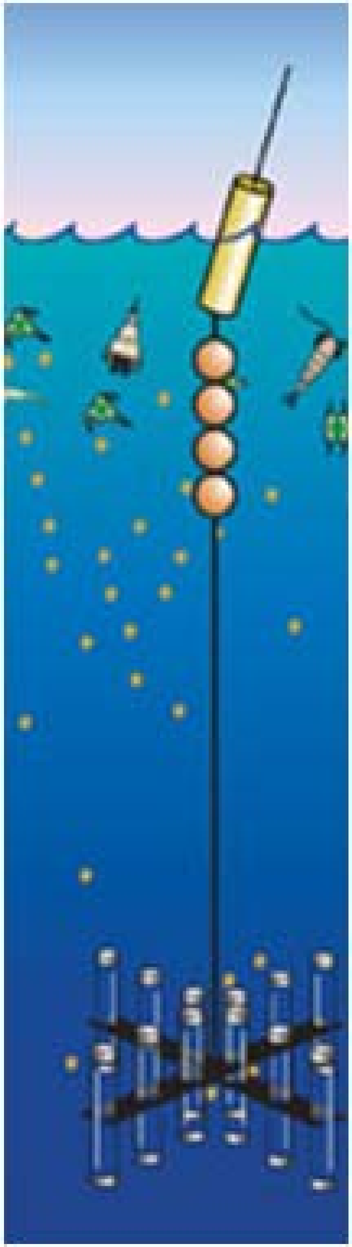
↓ Temperature

Martin's Iron Fertilization Experiments show this…

The Big Question: Can we assume this so that we can sell carbon credits?

CLIMOS

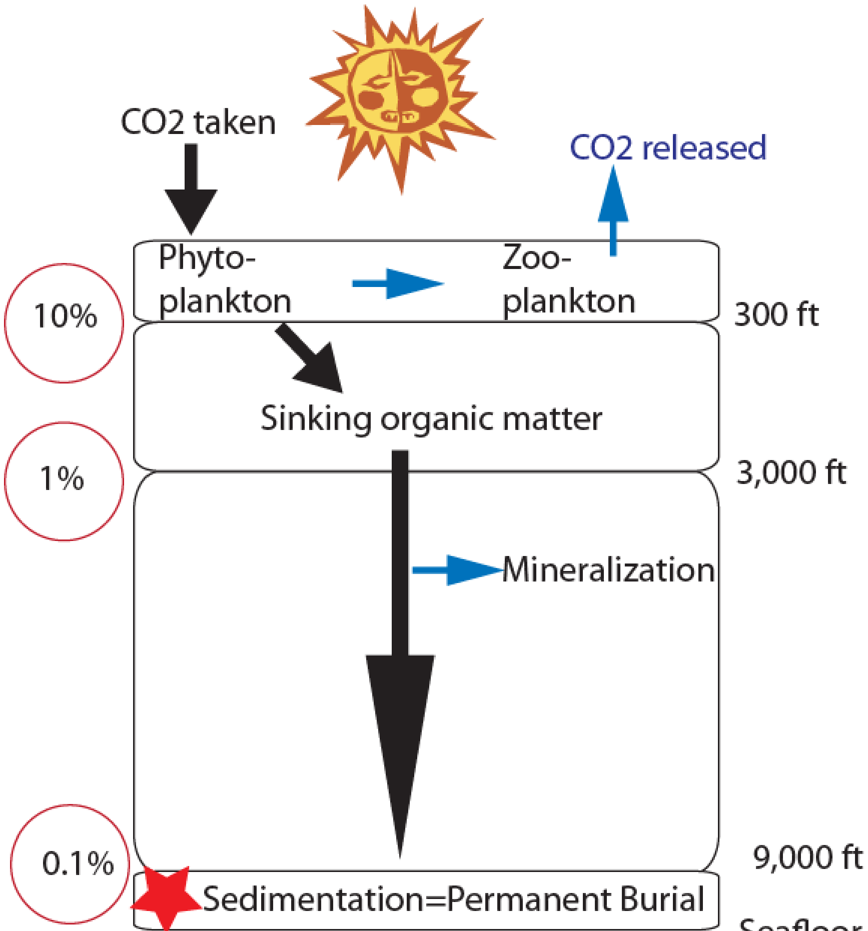
- Silicon Valley Startup Nov 2006
- Headed by Dan Whaley with Margaret Leinen as Chief Science Officer
- Looking at spots in Southern Ocean and Northwest Pacific Ocean
- Monitor carbon sequestration by
  - Sediment Traps
  - Measurement of water chemistry



CLIMOS

- Business Plan built around the sale of carbon credits
  - EcoSecurities and DNV working on Methodology
- Received 3.5 M in venture funding to fund envt’l impact statement and license application
- Need additional money to fund demonstration project

Permanent Burial?



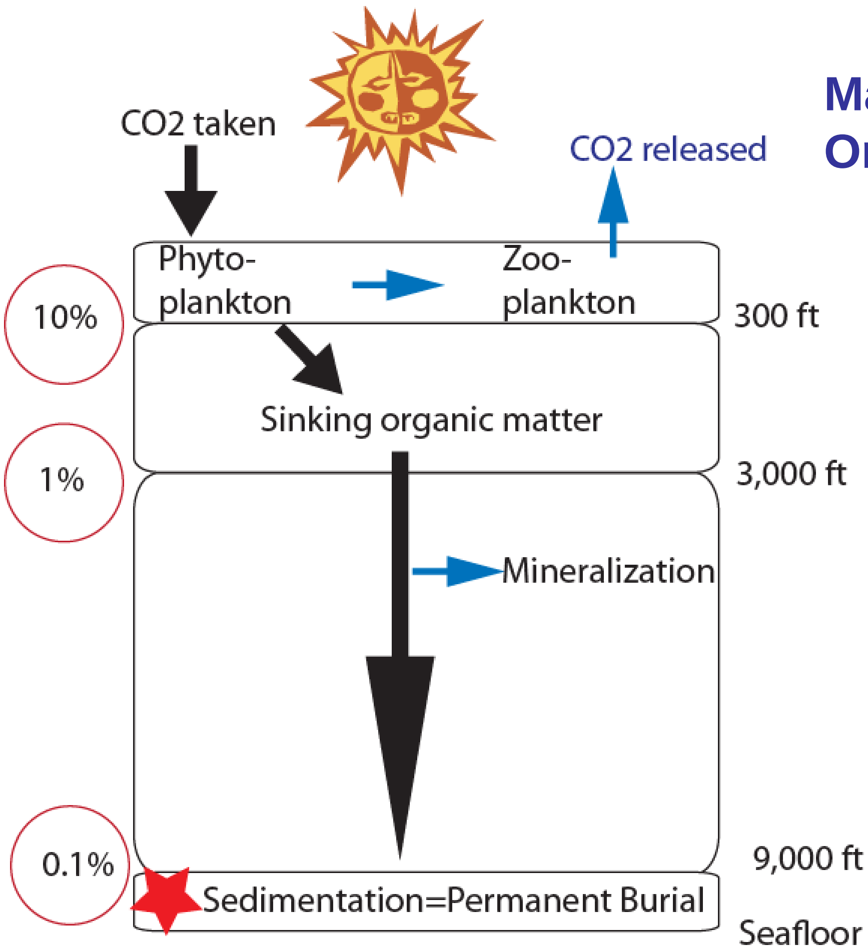
After Wright, 2003

Blue arrows:
Loss of CO_2 from export path

Most C, held in particulate organic matter, is "regenerated" as CO_2:

- Zooplankton grazing
  - Break up big particles
    - so they are less likely to sink
  - Eat phytoplankton
    - so they cannot sink
  - Excrete fecal pellets (small)
    - so they are less likely to sink
- Bacteria mineralization/ decomposition
- Dissolution

Permanent Burial?



After Wright, 2003

Martin's Curve of Remineralization of Organic Carbon at depth

Depth (m)	Organic C flux (Gt y^{-1})	Cumulative % regeneration
100	5.9	0
150	4.2	30
200	3.3	45
300	2.3	62
400	1.8	70
500	1.5	75
600	1.3	78
800	1.0	83
1000	0.83	86
1500	0.59	90
2000	0.46	92
3000	0.32	95
4000	0.25	96
5000	0.21	96

Martin et al., 1987

Permanent Burial?

Results from previous experiments

Experiment	Export Change
IronEX I	NC
IronEX II	Increase
SOIREE	NC
EisenEx	NC
SEEDS	NC
SOFEX-S	Increase
SOFEX-N	Increase
EIFEX	Increase
SERIES	Increase
SEEDS II	NC
SAGE	NC
FeeP	NC

12 Experiments:

- No Significant Change:7
- Increase: 5

Boyd et al., 2007

Did Fe-fertilization make a difference?

Southern Ocean Fe Experiment (SOFEX):

Most promising location, most reliable results

- CO_2 drawdown = that of natural blooms
- Effect was "small relative to global carbon budgets and proposed geoengineering plans to sequester atmospheric carbon dioxide in the deep sea" (Buesseler et al., 2004)
- Therefore *"Large-scale oceanic iron fertilization appears not a feasible strategy to sequester anthropogenic CO_2"* (Zeebe & Archer, 2005)

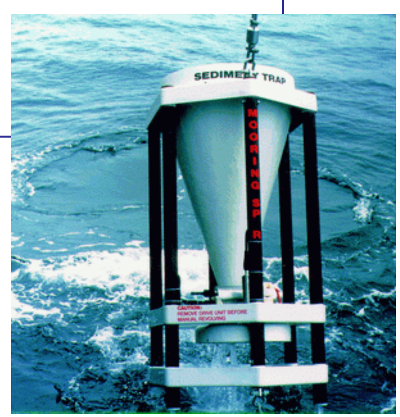
Quantifying Carbon Export: Sediment Traps

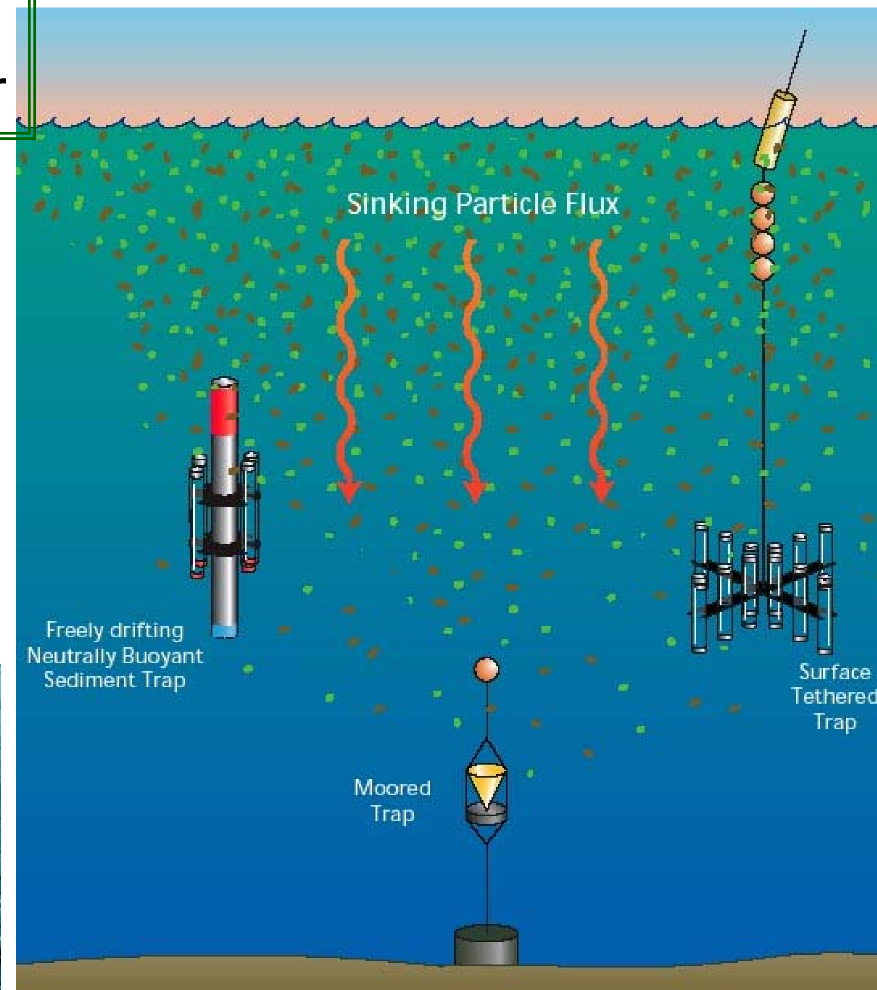
Most direct measurement of sinking particulate organic matter

Many Sources of Error:

- 10-1,000% of POM represented at 300 m
- No chemistry-based correction for flux
- Zooplankton: sinking or swimming?

De la Rocha, 2004





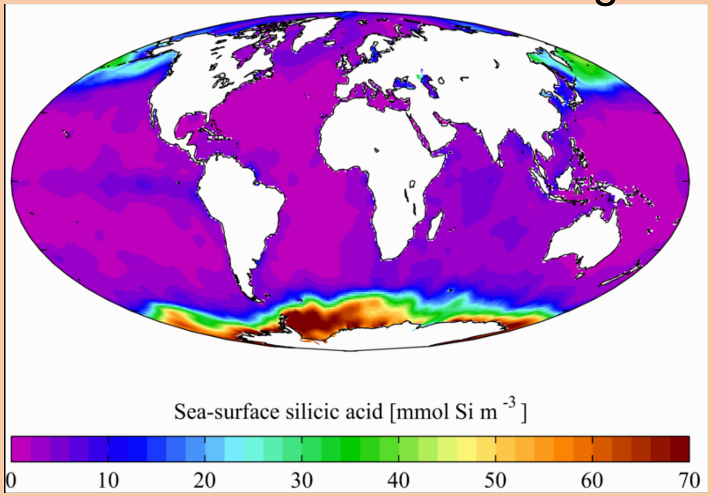
http://www.whoi.edu/cms/images/oceanus/2006/2/trap_diagram_n_19736.jpg

Export Efficiency: Effects of Silicic Acid

SILICIC ACID

- [SiOx(OH)4-2x]n
- Nutrient needed by some phytoplankton called DIATOMS (silica shells)

Low silicic acid limits diatom growth



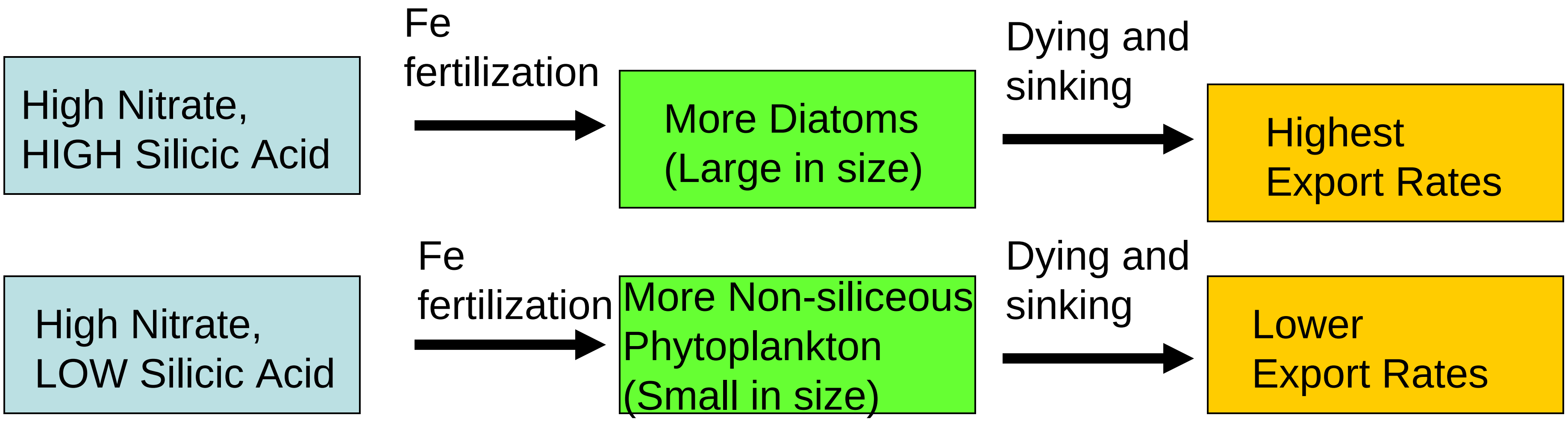
http://en.wikipedia.org/wiki/Image:AYool_WOA_surf_Si.png

http://photography.nationalgeographic.com/staticfiles/NGS/Shared/StaticFiles/Photography/Images/Content/diatom-shapes-527153-sw.jpg

Importance of Diatoms

- Only phytoplankton to use silicic acid
- Larger in size, sinks faster, better for C export (vs. non-siliceous phyto-plankton)

Export Efficiency



FACT: Export Efficiency depends on concentration of silicic acid in water.

PROBLEM: Most of the Southern Ocean (65%) is a low silicic acid area

Coale et al., 2004

Ecological Impacts: *Ecological Stoichiometry*

Redfield Planktonic Biomass Ratio = 1P : 16N : 106C

SOFEX

North Patch = 1P : 14N : 106C   Low Si

South Patch = 1P : 14N : 99C   High Si

Nutritional impact?

↓ N in plankton ⟶ ↑ # of plankton required by consumers?

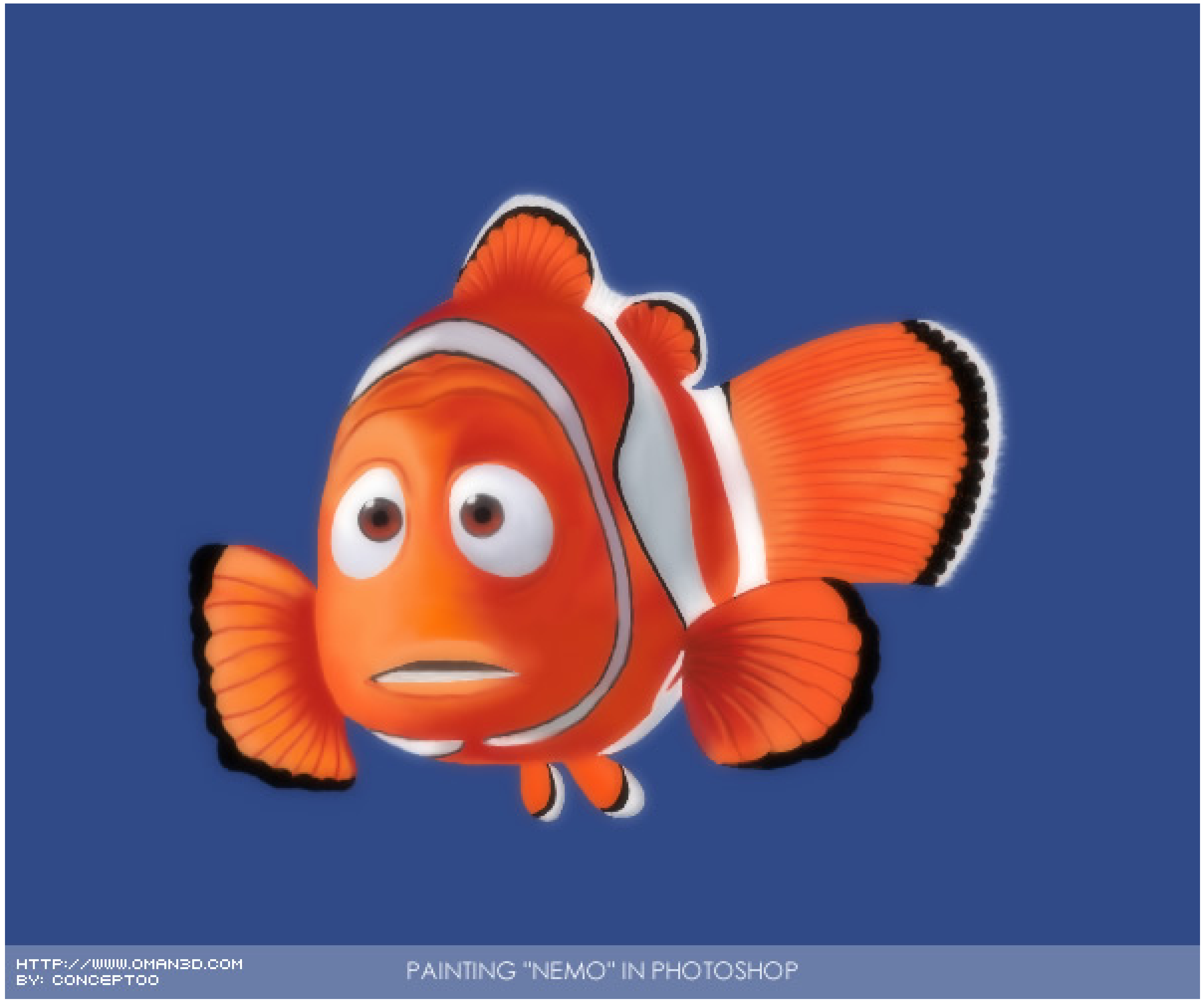
Variable biodiversity: long term effects to food web?

↑ Fe in High Si ⟶ ↑ Diatoms ⟶ ↓ Carbon Ratio

(Hiscock and Millero., 2004)

Ecological Impacts: *Biodiversity*

- What about the fishes?



- No studies beyond the base of food web

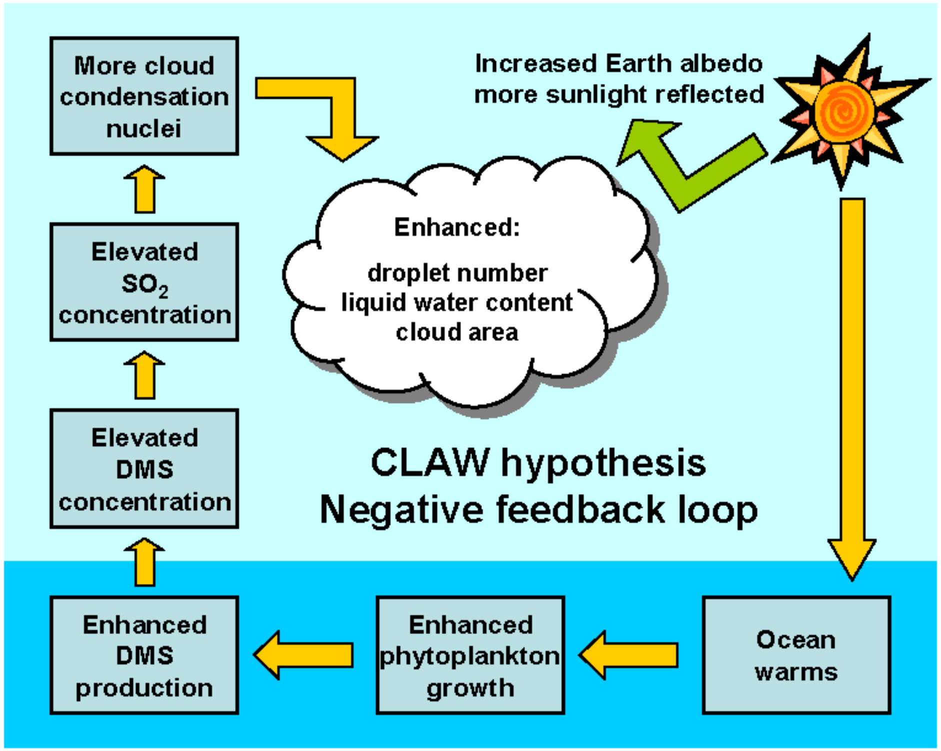
Ecological Impact: Issues of high productivity

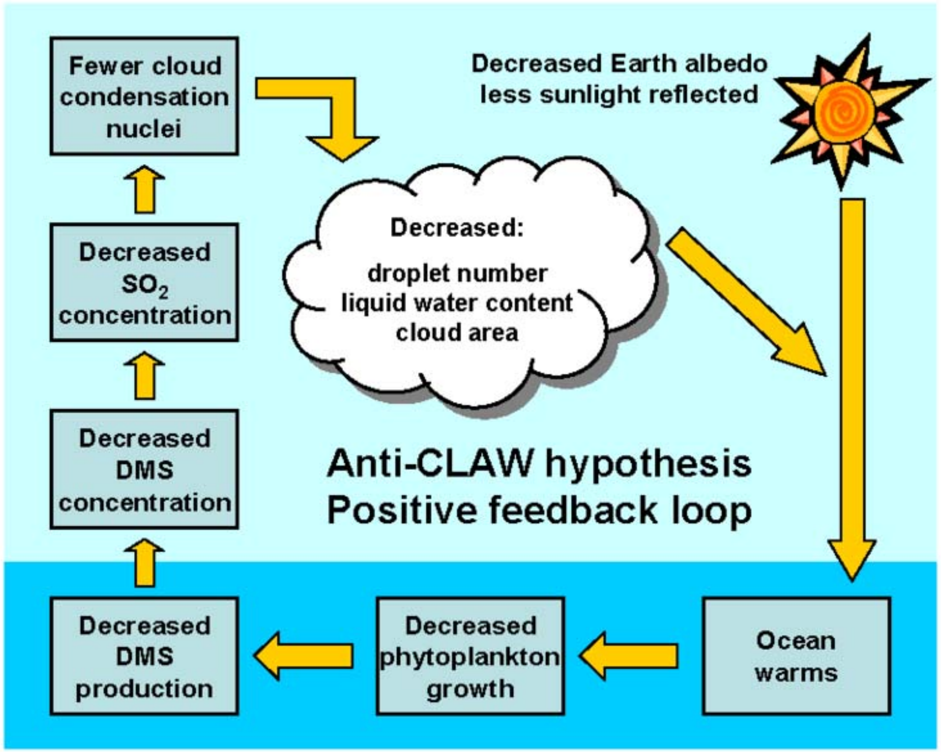
- Nitrous Oxide (310 ×'s GHWP)
  - Product of Zooplanktonic Metabolism

We currently lack reliable quantitative measurements of these phenomenon.

- Upstream removal of macronutrients
  - Decrease in downstream productivity?

Ecological Impact: *Dimethylsulfide (DMS)*





(Charlson et al., 1987)

(Lovelock, 2007)

CLAW: Charlson, Lovelock, Andreae, & Warren

Other considerations:

- Legality
  - London Convention ('72) & Protocol ('96)
  - Climos: We are not dumpers

- Logistics (Southern Ocean)
  - Roaring 40's & Furious 50's
  - Seasonally Limited
  - Geographically Remote

(British Antarctic Survey)

Recommendations:

We must meet these scientific objectives:

- Prove that *significant* amounts of CO_2 are *permanently* sequestered
- Investigate potential chemical and biological side-effects
- Determine how effects of fertilization change between locations and over time

Recommendations to meet objectives:

1) Refine sediment trap designs
    - Eliminate error in C flux measurements to get most accurate idea of Fe-fertilization potential
2) Improve modeling capability for Fe-fertilization
    - Most remaining questions regarding Fe-fertilization pertain to experimental area and duration
    - Models allow us to assess effects of long-term and large-scale fertilization, without risks of side-effects
3) Implement large-scale, long-term, publicly funded research/demonstration projects

Conclusions

- Fe-fertilization has the ***POTENTIAL*** to be one of many "wedges" in combating climate change
  - Other alternatives to business-as-usual must also be considered to decrease atm. CO_2
- Until recommended scientific objectives are met, Fe-fertilization is not ready for commercial practices

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