Carbon sequestration through iron fertilization: A review of the major issues

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Outline

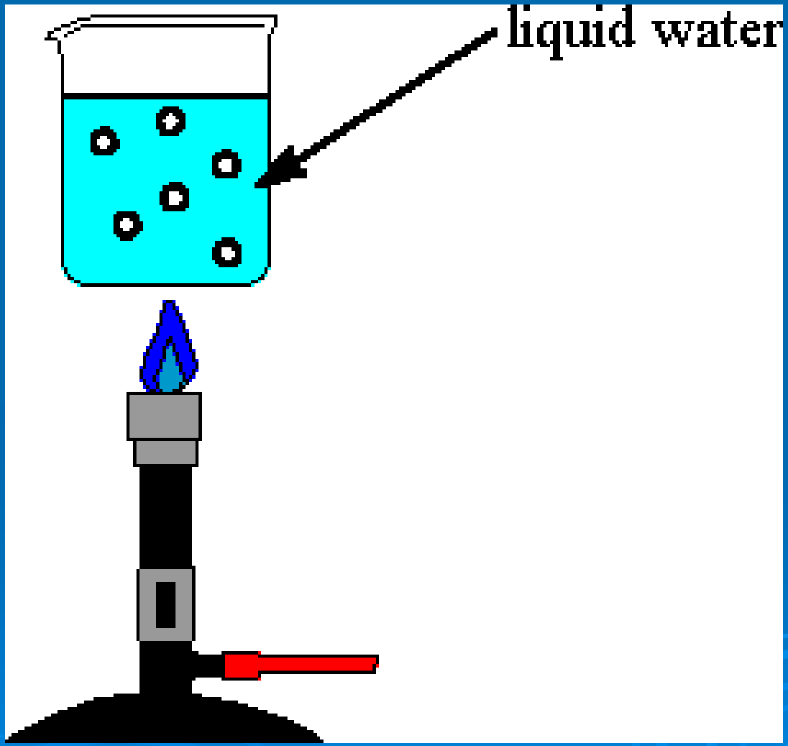
- Why does the ocean hold so much carbon?
- Why the speculation that iron fertilization could increase this amount?
- What are some of the practical issues surrounding iron fertilization as a carbon sequestration strategy?
  - Verification
  - Consequences

How do you know when water on the stove is getting hot?

Bubbles appear in the fluid.

Dissolved gas comes out of solution.

~20 μM of CO_2 dissolves in water



http://www.chem.purdue.edu/gchelp/liquids/boil.html

How much carbon does this mean the ocean should hold?

$1\mu M$= 1 millimole/m^3

=1 megamole/km^3 = 12 tons C/km^3

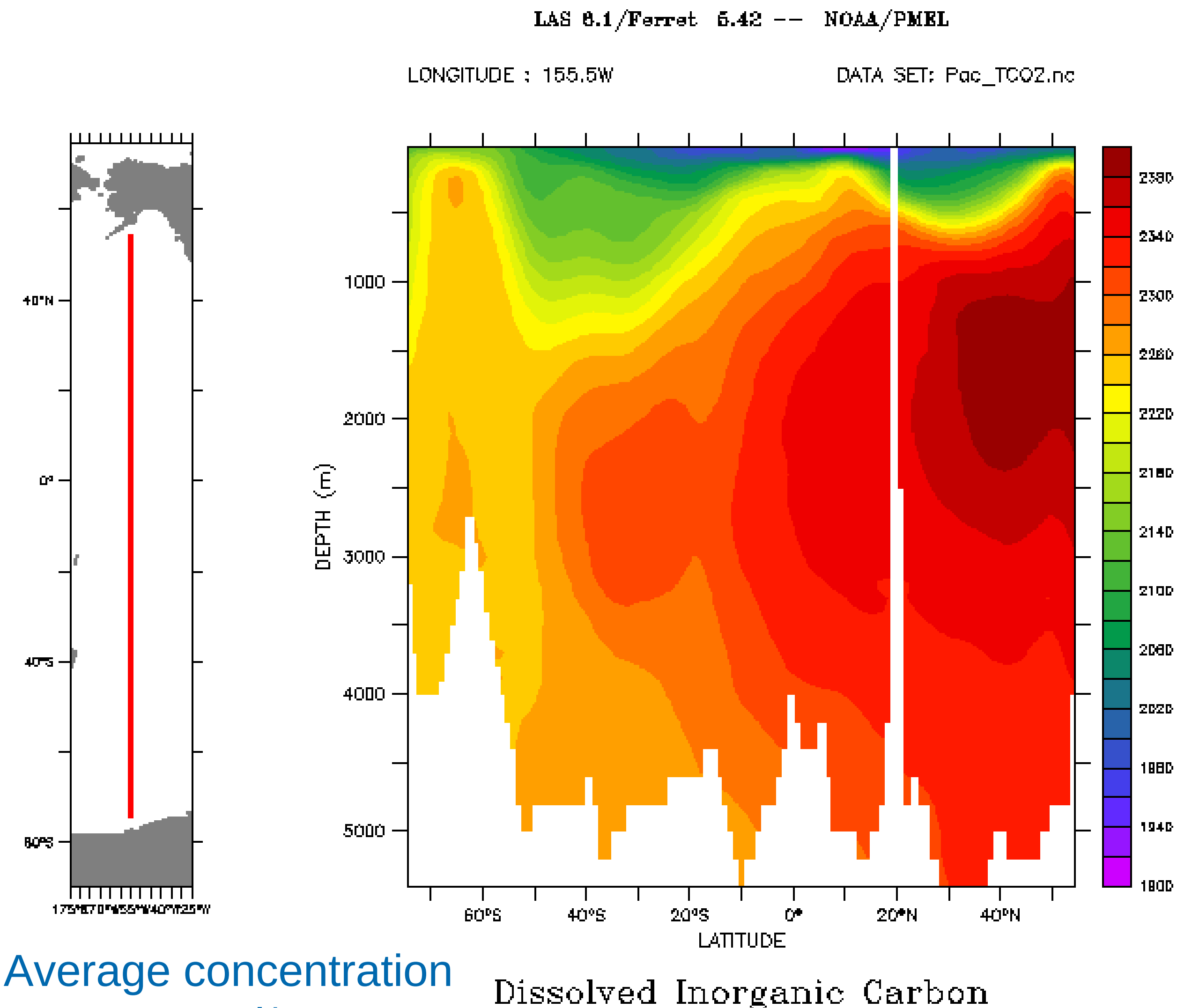
Ocean area is about 360,000,000 square km.

Depth is about 4km.

Volume = 1.44 billion cubic km

1 millmole/m^3~ 17 billion t C or 17 Gt C => 20 μM =340 GtC

How much carbon does the ocean actually hold?



Average concentration ~2000 mmol/m3!

Ocean actually holds about 34000 GtC!

Atmosphere only holds 800 GtC.

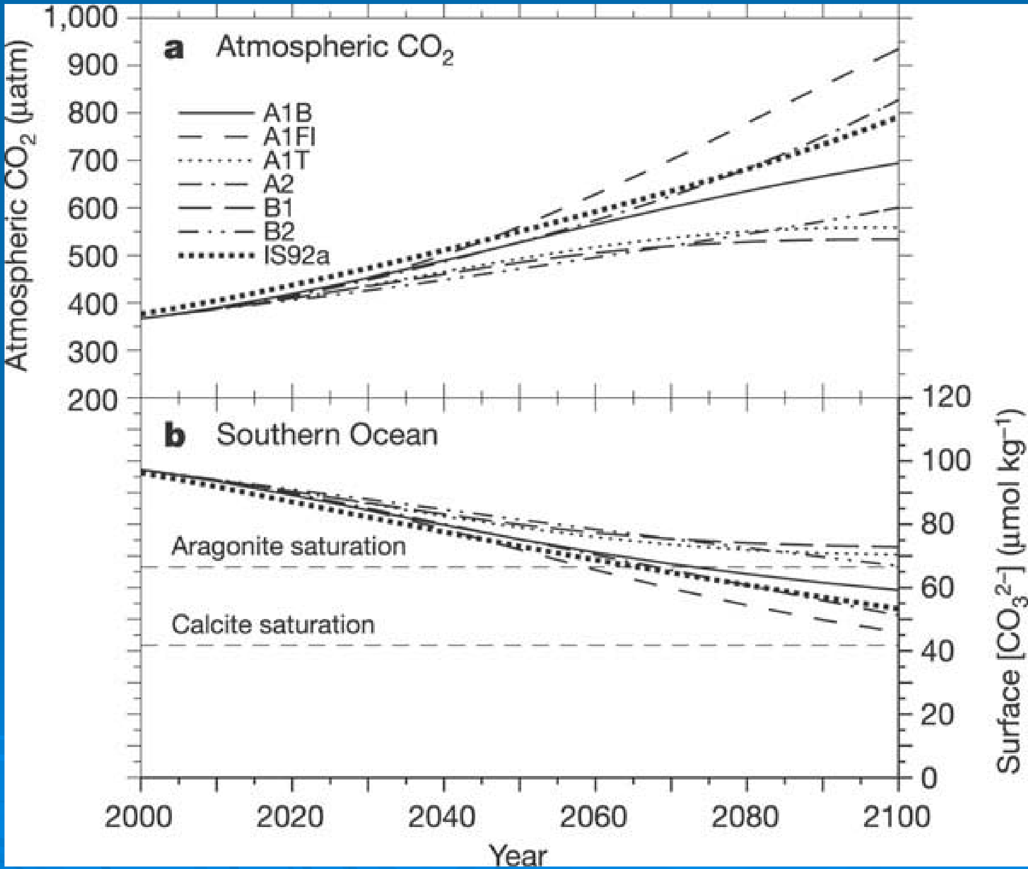
What form is this carbon in?

Why so much carbon?

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrow 2HCO_3^-$$

1. Ocean can hold a lot of carbon- because carbon dioxide is buffered by carbonate ion.

2. Increasing carbon dioxide will result in reducing the amount of carbonate ion (ocean acidification).

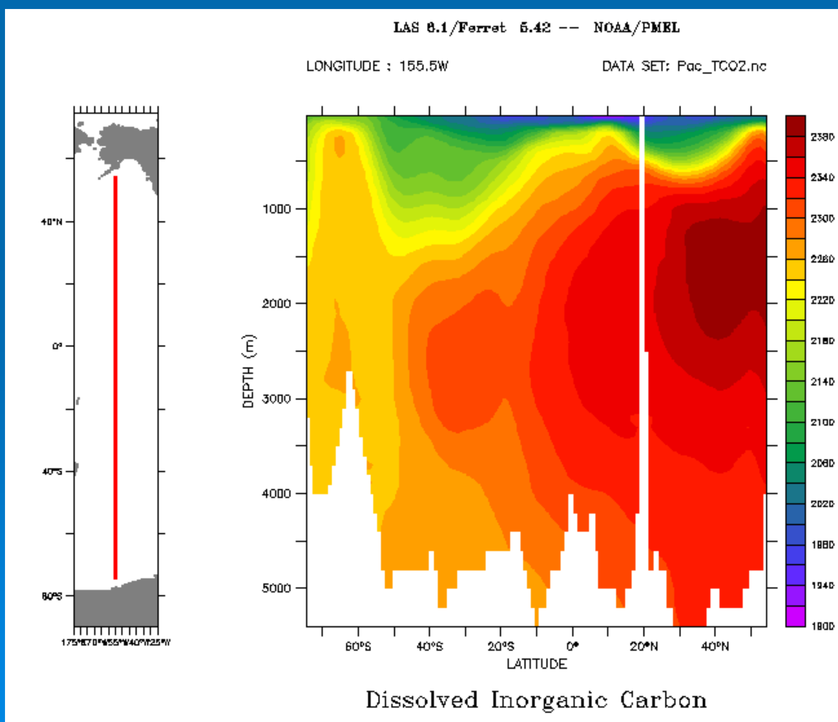


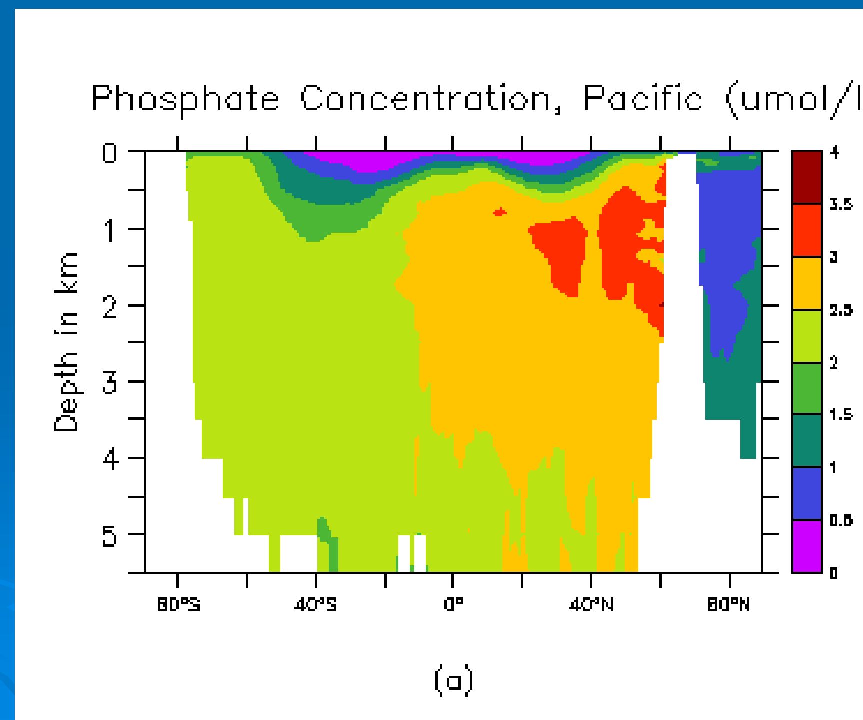
Orr et al., Nature, 2005

Role of biology

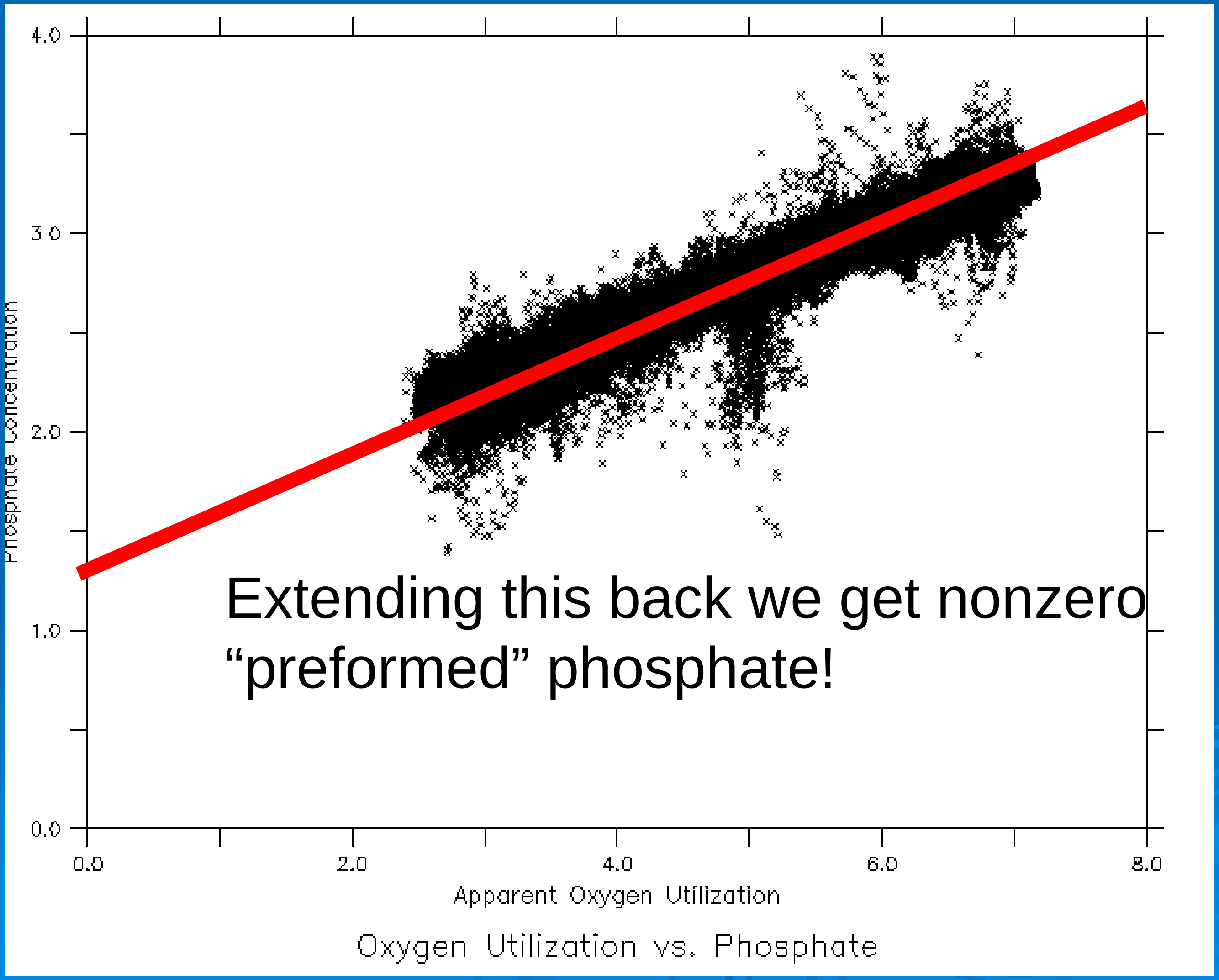
$$117*(CO_2 + H_2O) + 16NO_3 + PO_4 \xrightarrow{light,iron} 117*(CH_2O + O_2) + \text{Organic Matter}$$

Nutrients are released, oxygen consumed when reaction runs backwards.

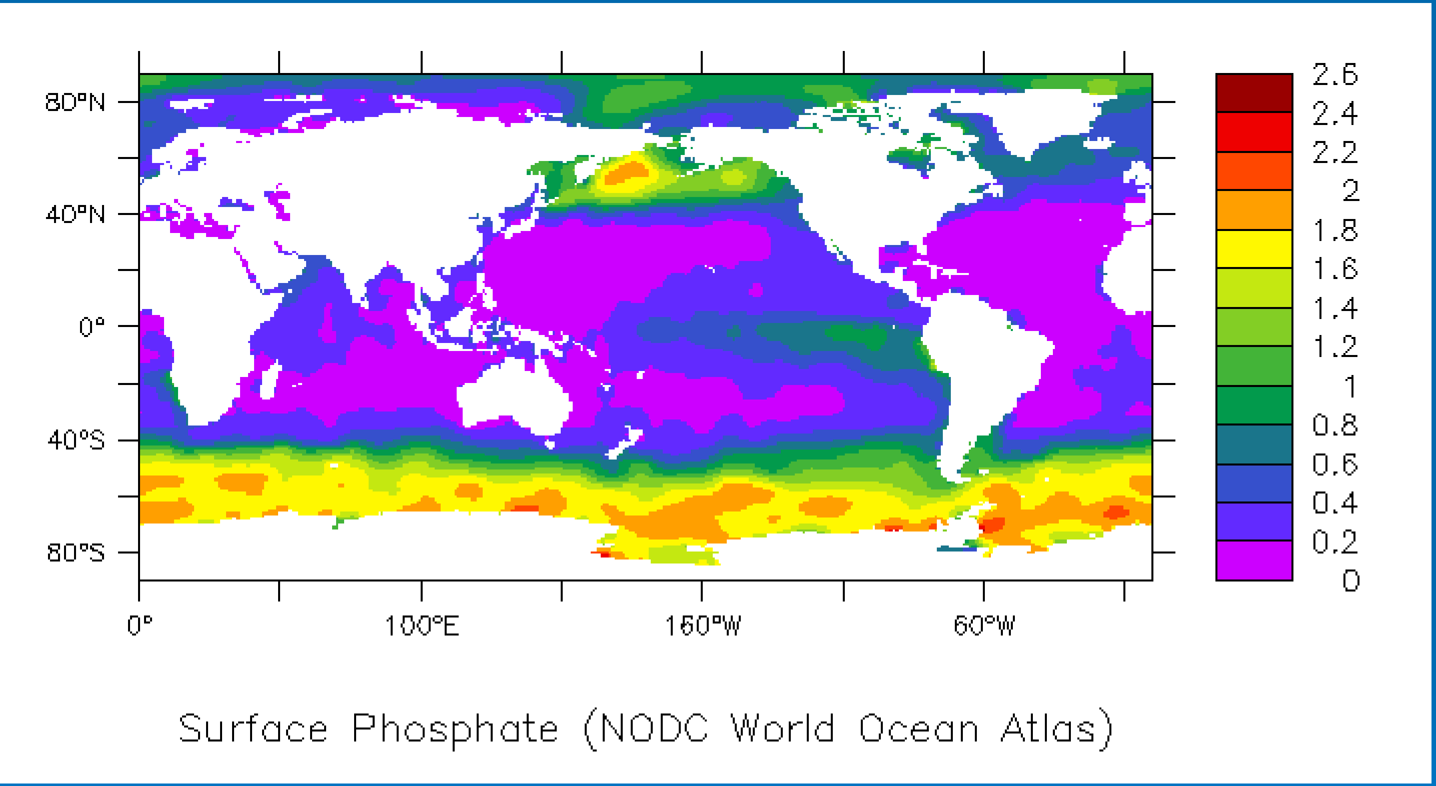




How much phosphate is associated with carbon?- Look at deep oxygen



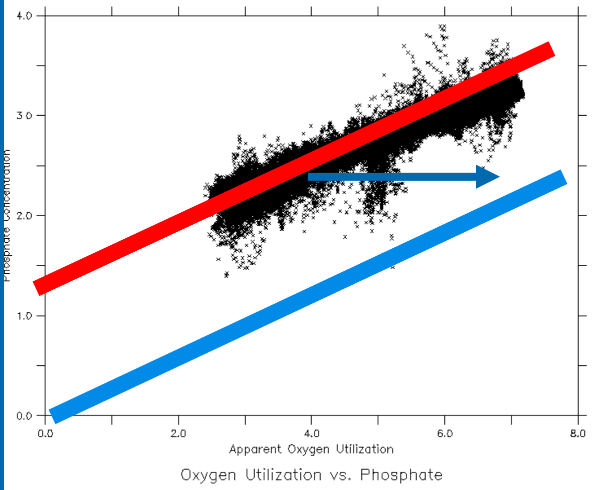
High preformed nutrients= high surface nutrients



Points to dominant role of Southern Ocean, potential role for other regions.

So ocean could hold more carbon…

0.1 mmol/m^3 phosphate = 11.7 mmol/m^3 C



~200 Gt C ~90 ppmv (!)= 900 ppmv/μM

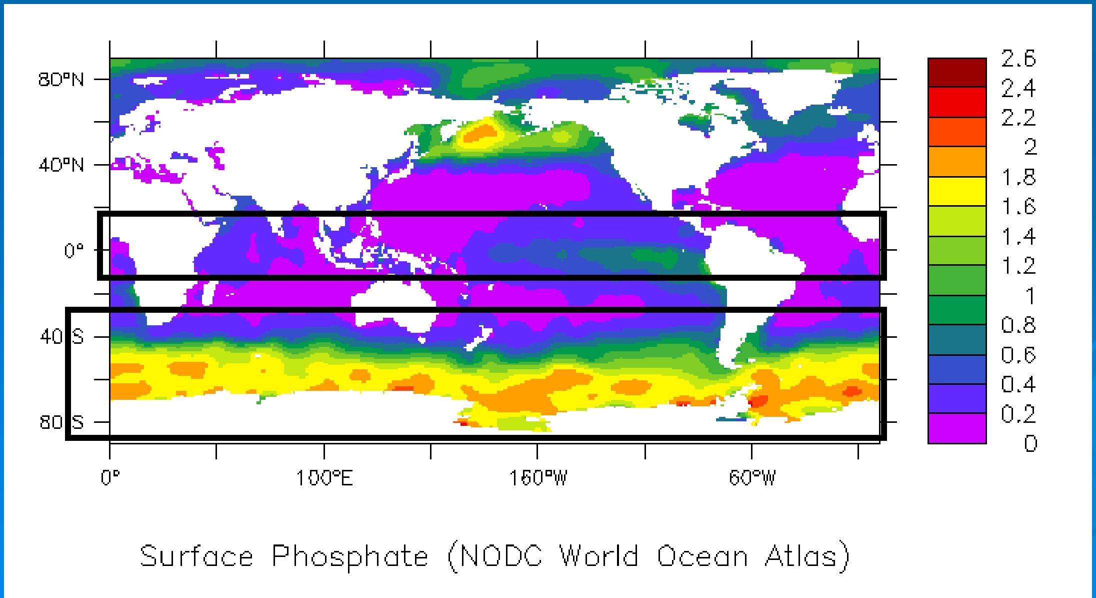
But… remember the buffering equation

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrow 2HCO_3^-$$

So over a long time, much of the response to changing preformed nutrients will be compensated.

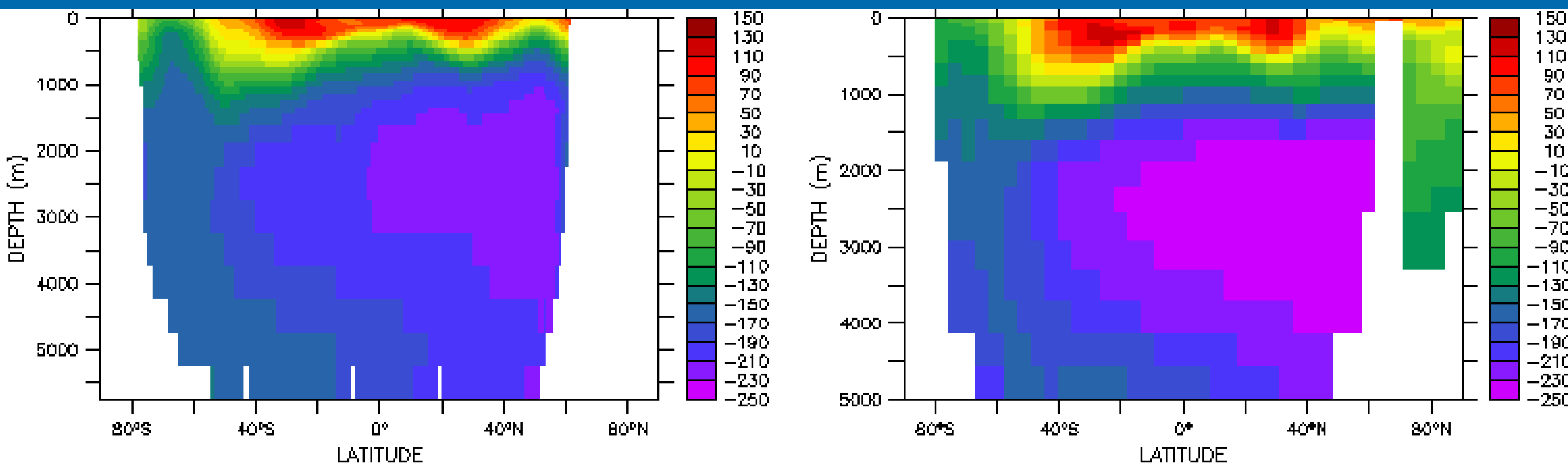
What can models add to this?

- Role of *different regions*
- *Time scale* of change compared with buffering.
- *Relationship* between reduction in CO_2 and increase in sinking organic matter.



Diagnostic ocean models

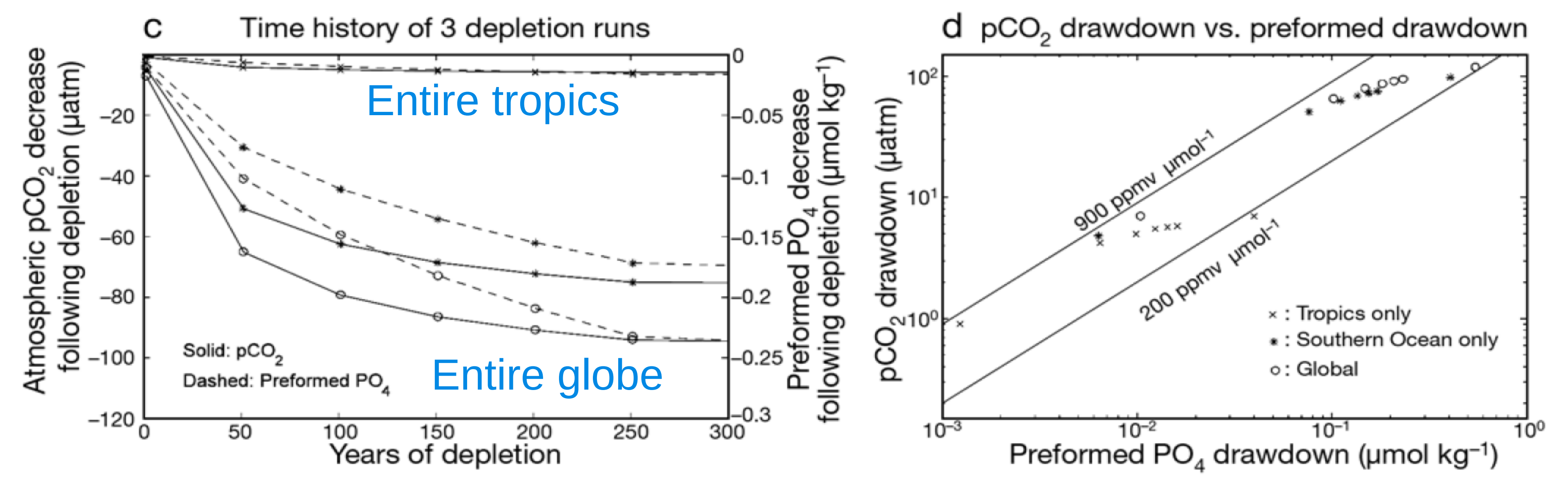
- Restore ocean surface to observed values of T,S, nutrients.
- Apply “observed” fluxes of momentum, heat, freshwater
- Predict internal structure, flows using dynamics.
- Run depletion scenarios setting nutrients to zero



C14, Pacific Sector

C14, Model

Preformed nutrient changes and carbon drawdown



Gnanadesikan and Marinov, MEPS, 2008

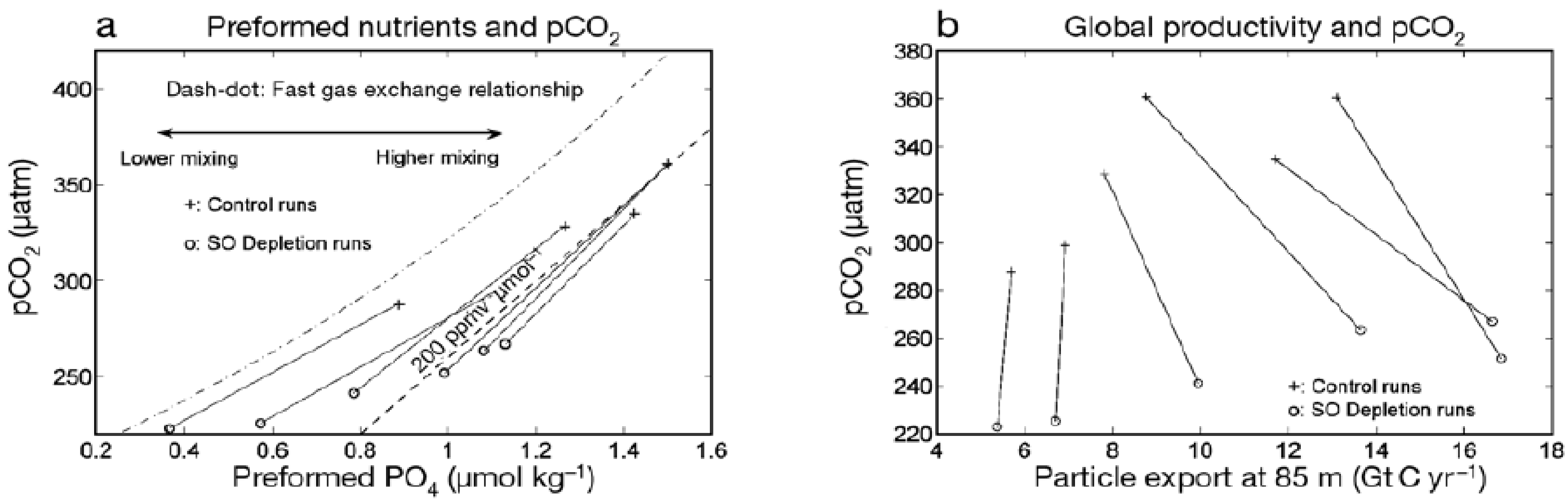
Larger preformed nutrient drawdown results in larger carbon drawdown.

Southern Ocean dominates.

Long time scales required to get large impact on atmospheric CO2.

Significant compensation over century time scales.

Runs with different models show no necessary relationship with global export!



Gnanadesikan and Marinov, 2008

Equilibrium response is well characterized in terms of **preformed nutrients**, poorly characterized by looking at export alone.

Summary: Ocean carbon cycle

- Ocean holds a lot of carbon because of carbonate buffering.
- Biology adds additional carbon to the system…
- But it is inefficient, because not all the nutrients in the system get used.
- If we could associate some of these nutrients, the result would be to reduce atmospheric CO2.
- Over time, response is buffered by ocean.

What's the connection with iron?

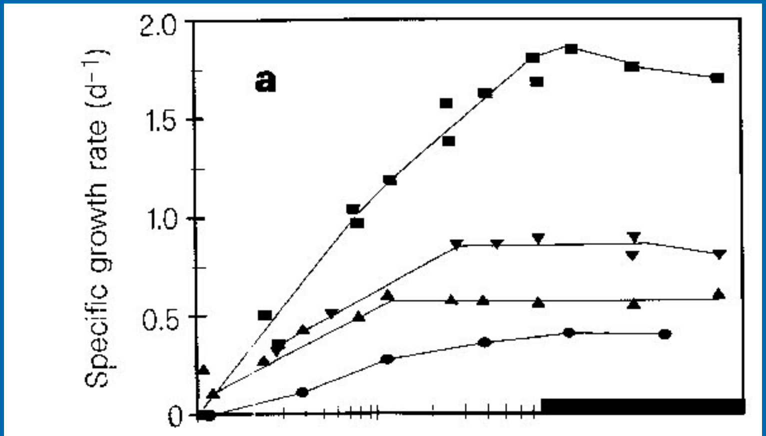
Metalloenzymes involved in

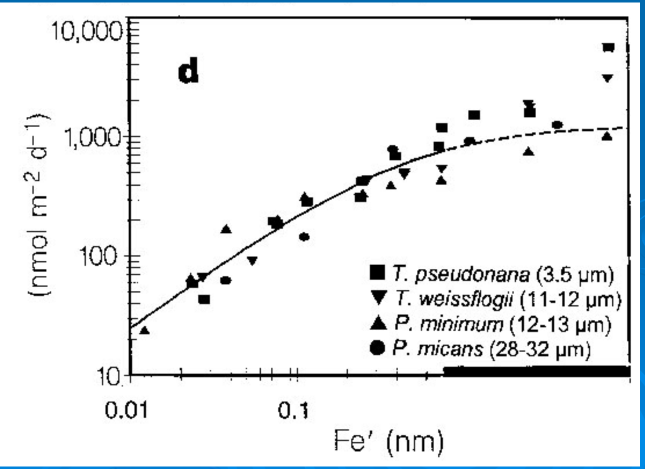
- Photosynthesis
- Nitrate reduction

Lab culture studies show increased growth rates with increased levels of iron.

Fe:P ratios~ 1:1000

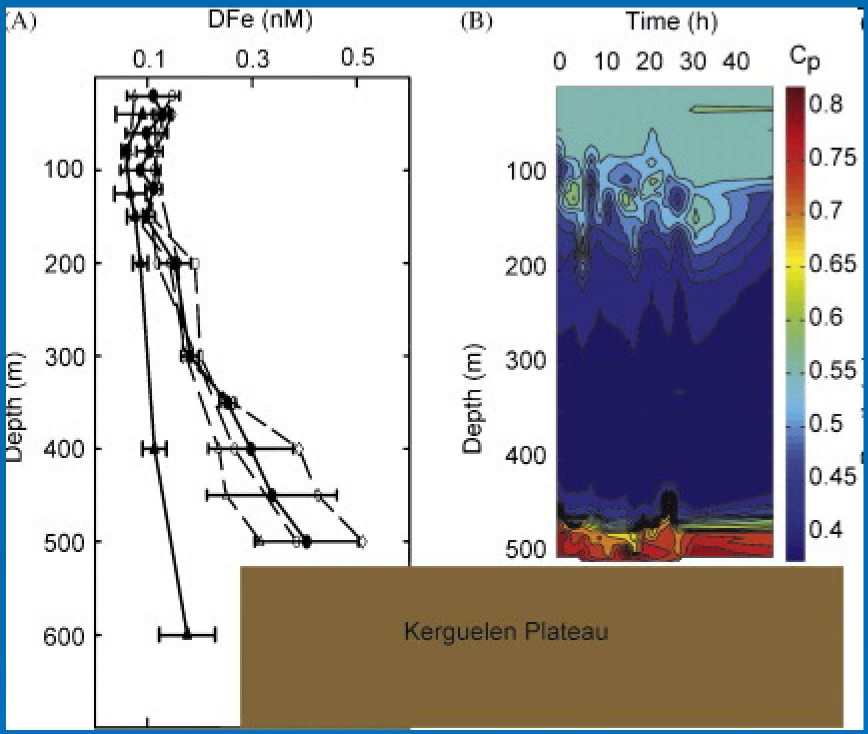
Fe:C ratios ~ 1:120,000





Sunda and Huntsman, Nature, 1997

Why is iron rare in the ocean?



Enough iron is found in surface waters to take up 0.1 mmol/m^3 phosphate.

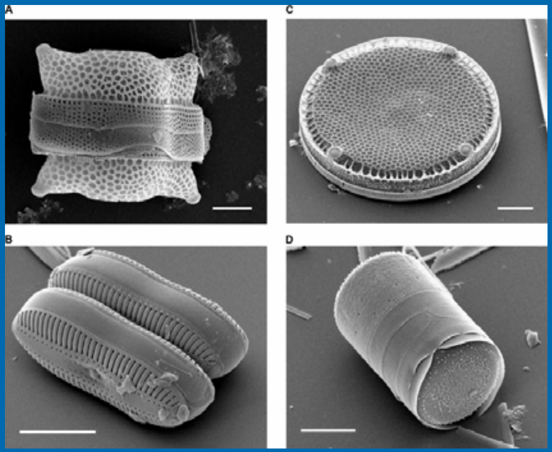
Higher values at depth are associated with topography- not higher nutrients.

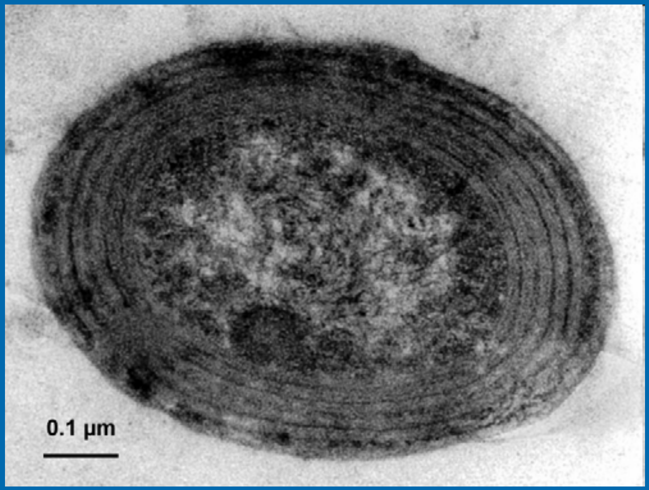
Iron is preferentially stripped out by sinking particles.

Blain et al., DSRII, 2007.

Implications

Big cells (with low surface area to volume ratio) need a lot of dissolved iron.





These cells tend to be more efficient at exporting carbon

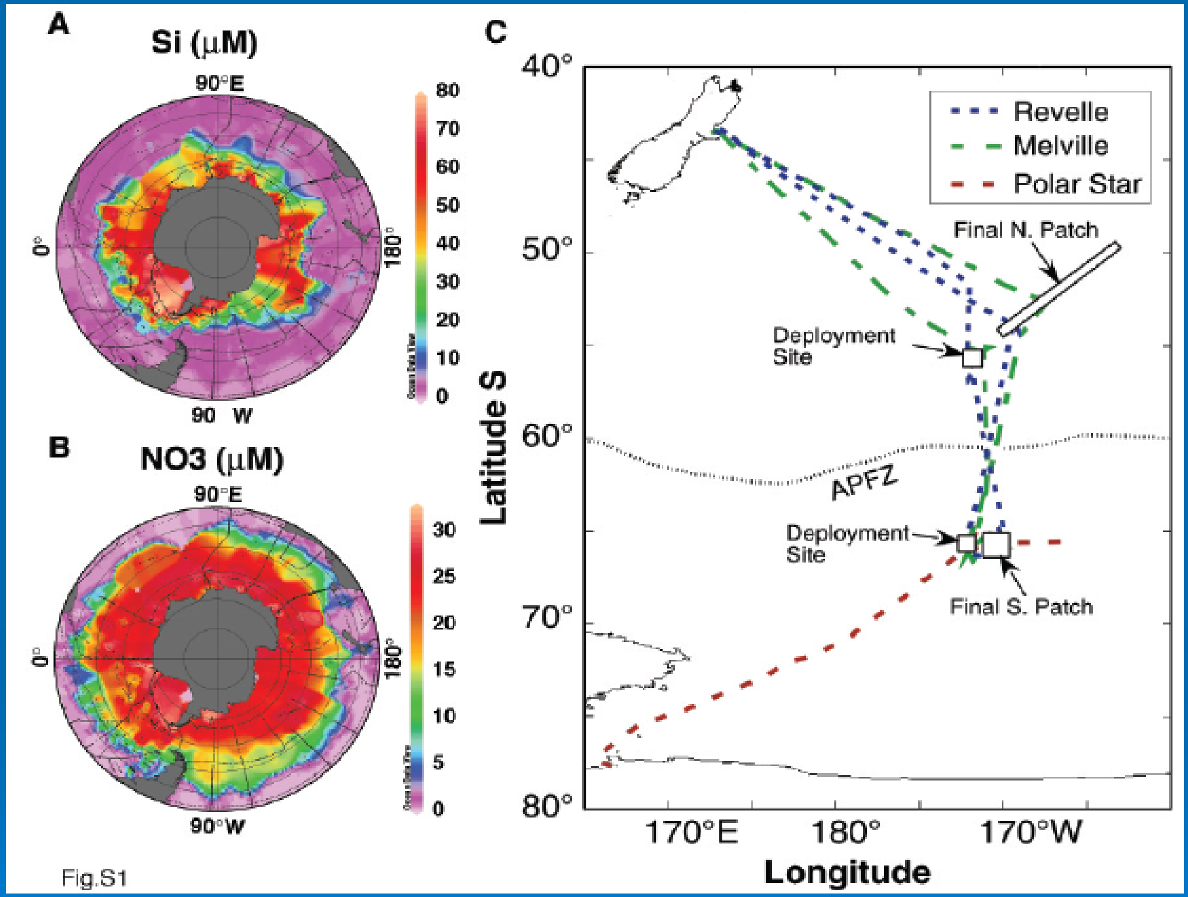
10 micron scale bar

0.1 micron scale bar

Small cells can survive at lower levels of iron, but tend to be tightly coupled to grazing.

Iron could explain High Nutrient Low Chlorophyll Regions!

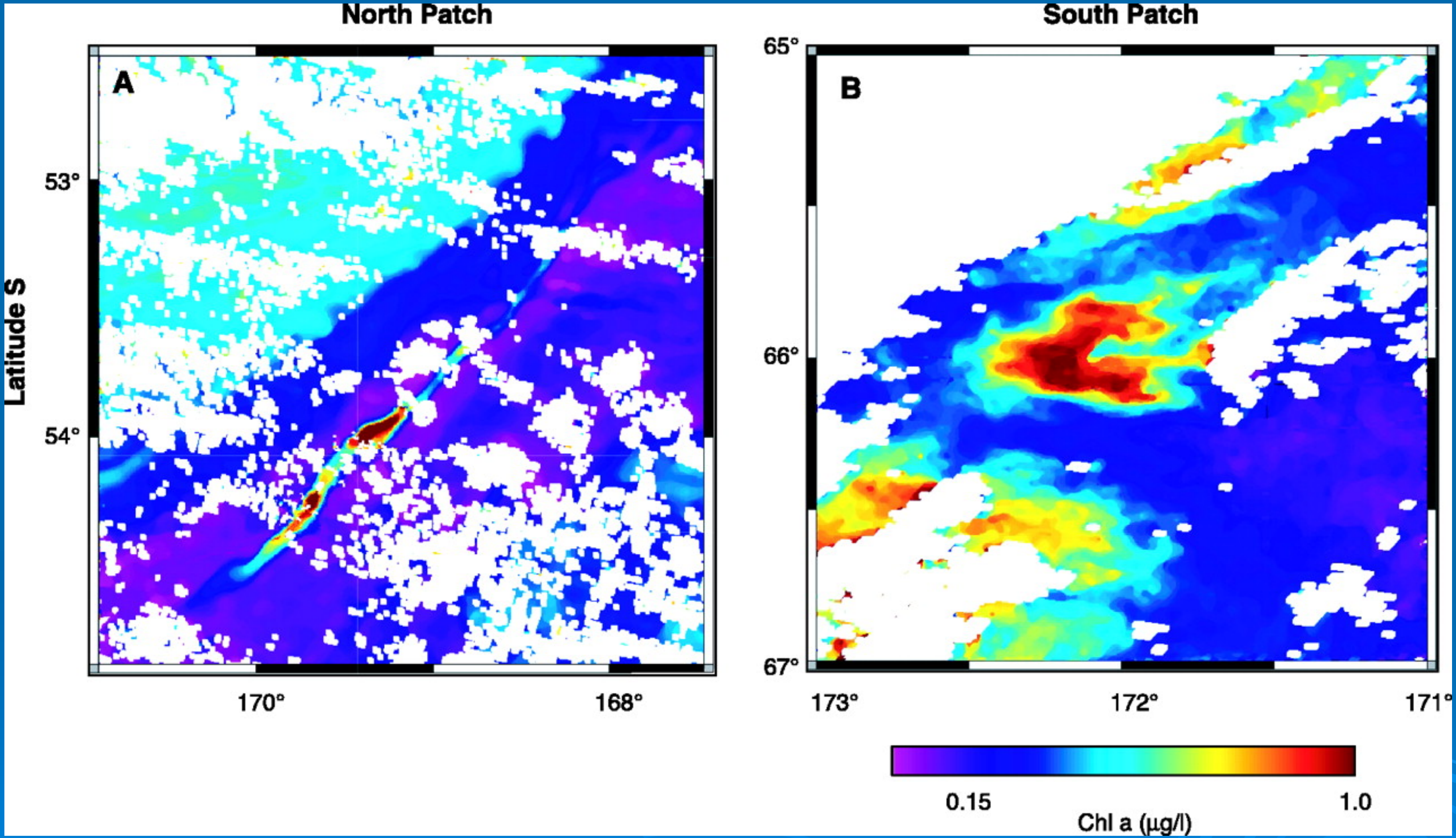
SoFEX experiment



Photos: K. Buesseler

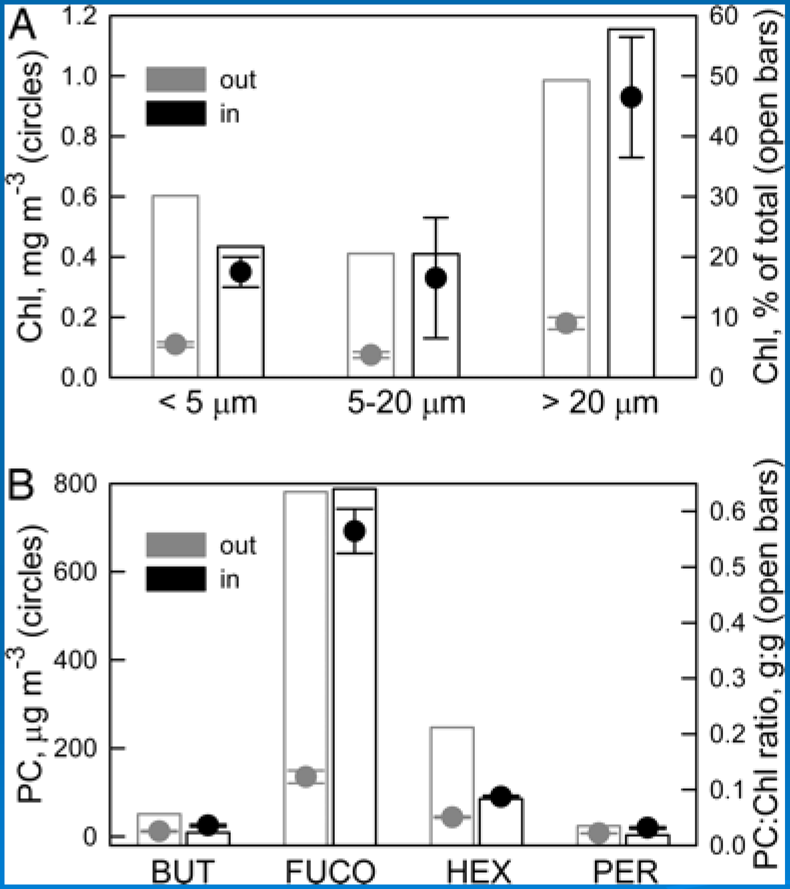
Led by Ken Coale (Moss Landing), Supported by NSF and DOE, with participation from NOAA/AOML.

Results: Increased chlorophyll



Coale et al., Science, 2004.

Less evidence for changes in species composition



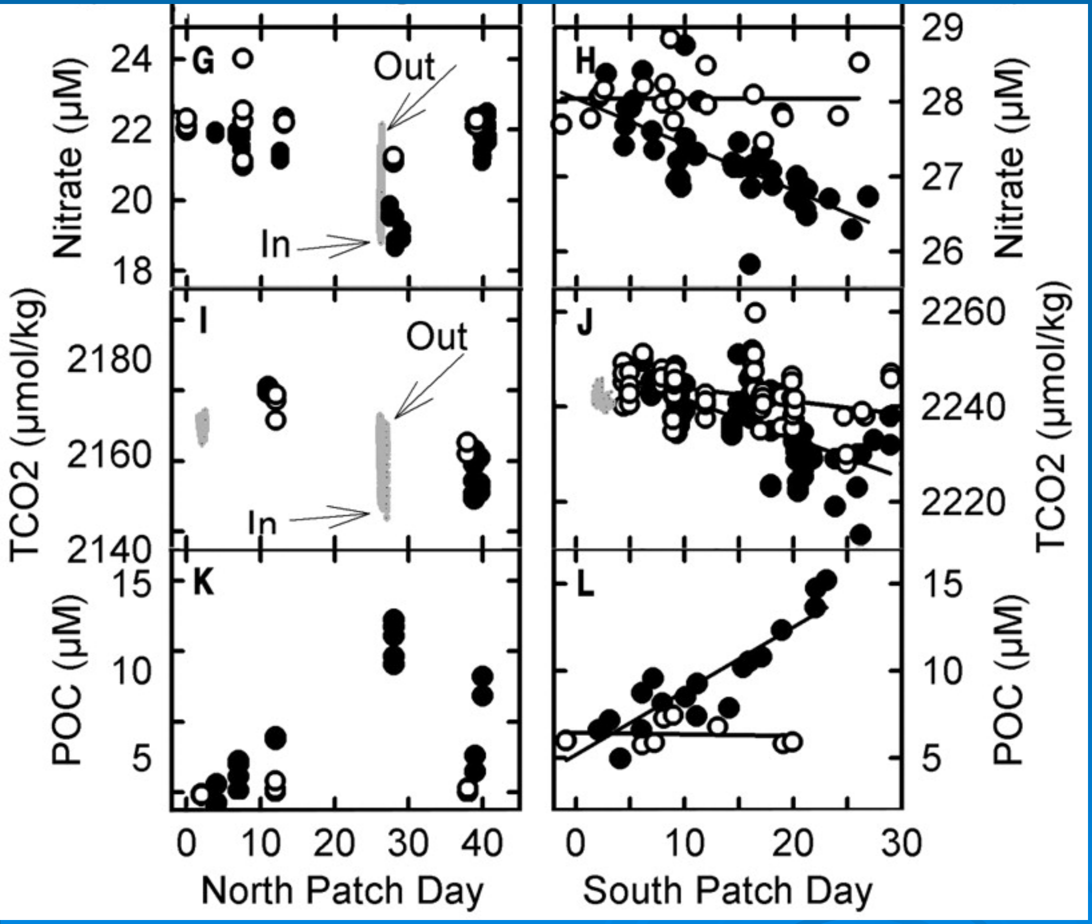
Bars show fraction of species by size and pigment. Small changes seen inside and outside the patch.

Circles show absolute concentrations of Chl and particulate carbon. Large changes inside and outside the patch.

Hiscock et al., PNAS, 2007

Clear evidence for changes in nutrient uptake

Inside the patch relative to outside…



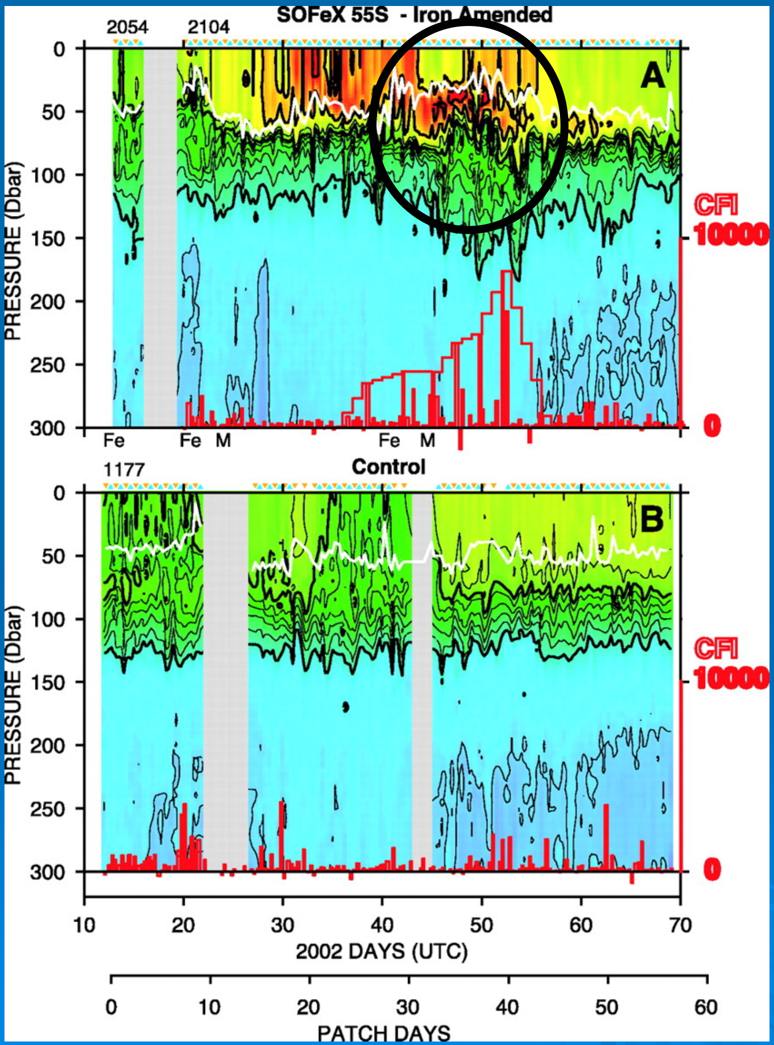
Nutrients go down.

Total CO2 is lower

Particulate carbon is higher.

Coale et al., Science, 2004

Some increased export

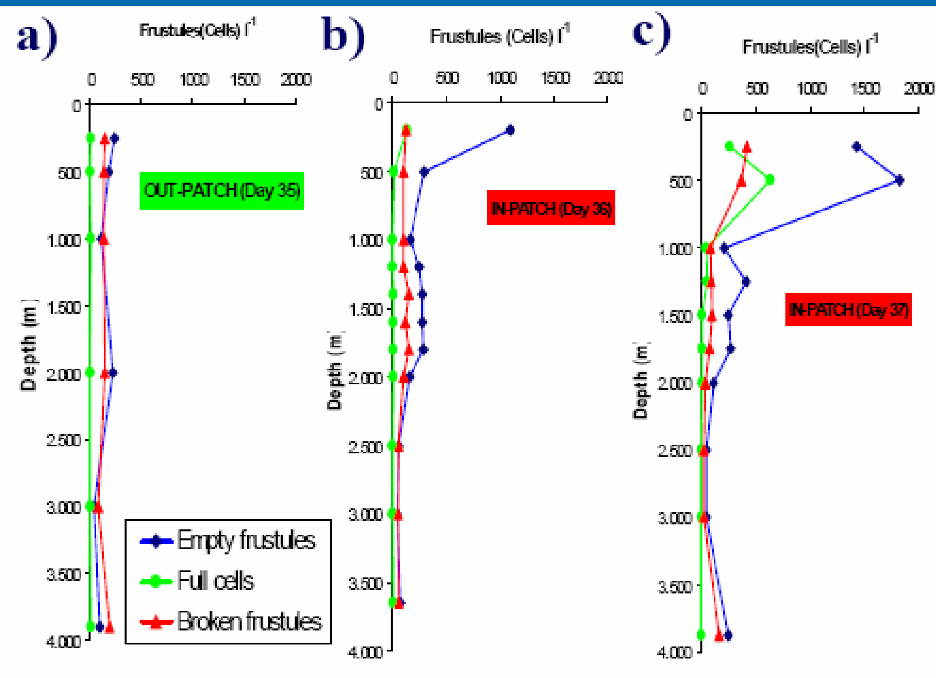


Bishop et al. (Science, 2004) shows results from two profiling floats, one inside the patch, the other outside.

Color contours show increased particulate matter inside path and increased export…

BUT…. export doesn't go very deep.

Counterexample- EiFeX



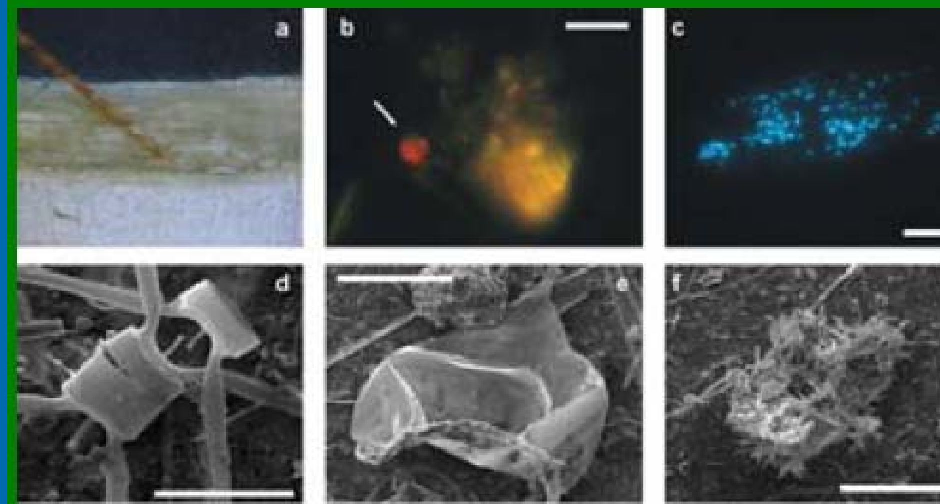


Fig. 5: Evidence of freshly deposited material underneath the EIFEX area (a-f): a) Sediment core with a 5 mm thick fluff layer. b) Chl-a fluorescence (arrow) of an intact dinoflagellate cell in ~3600 m; scale bar: 50 µm. c) High bacterial activity on a colonised cell of *Corethron* sp. in the fluff layer; scale bar: 50 µm. d) SEM micrograph of an intact chain of *Chaetoceros atlanticus*; scale bar: 20 µm. e) Lorica of the tintinnid ciliate *Cymatocylis* sp.; scale bar: 50 µm. f) fecal pellet containing diatom debris; scale bar: 100 µm.

Assmy et al., 2006

In this experiment a substantial amount of material appears to have gone right to the bottom!

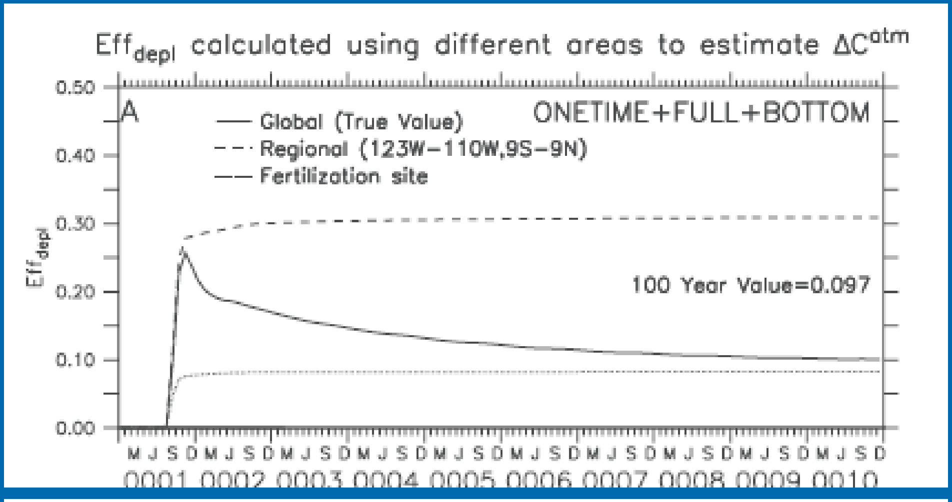
Summary: Iron fertilization

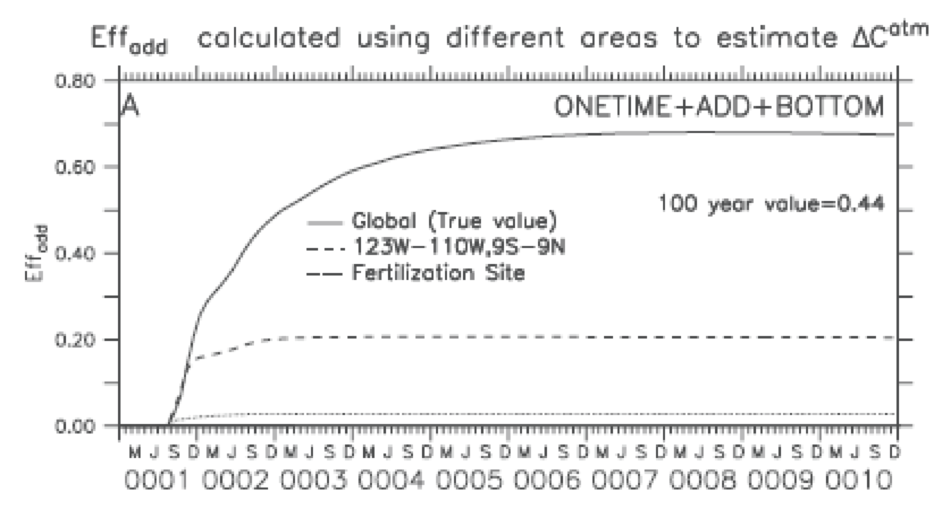
- All experiments to date have seen a bloom.
- Nutrients are drawn down in the bloom region.
- Very few experiments have stayed around for long enough to see increased export.
- Unclear whether export changes are significant- and therefore how long term changes in surface nutrients are likely to be.

Additionaly potential issues regarding fertilization?

- Can it be verified?
- Will it change ocean chemistry?
  - Oxygen
  - Other greenhouse gasses
- Will there be downstream consequences on ecosystems?
  - Reduced/increased production downstream
  - Toxic algal blooms

Problems with verification- patch fertilization simulations





Gnanadesikan, Sarmiento and Slater, Global Biogeochemical Cycles, 2003.

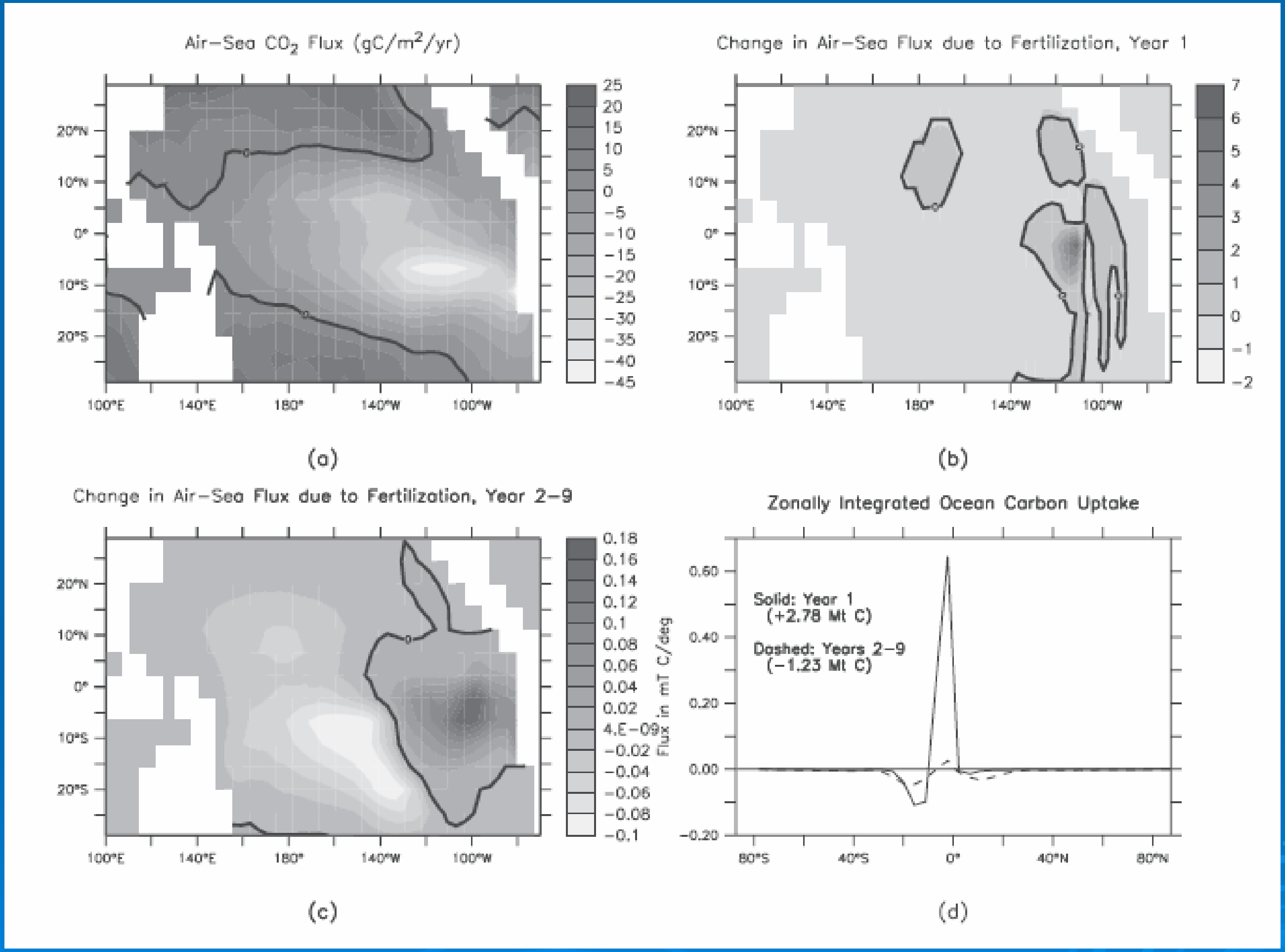
Simulation in which restoring value for nutrient is set to zero for one month, then returned to climatology (added iron quickly lost).

Simulation in which we add "supernutrient" to system (added iron always retained).

Result of fertilization depends on behavior of iron.

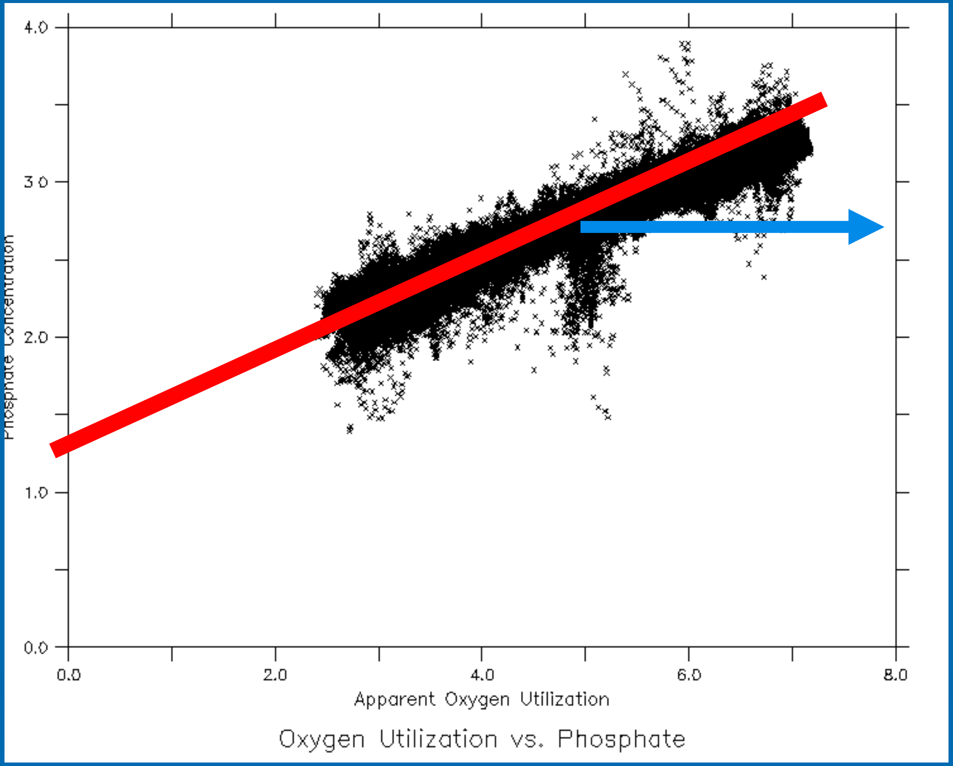
Local fluxes insufficient to get total flux.

Distribution of gas exchange resulting from patch drawdown



Gnanadesikan, Sarmiento and Slater, Global Biogeochemical Cycles, 2003.

Problems with ocean chemistry

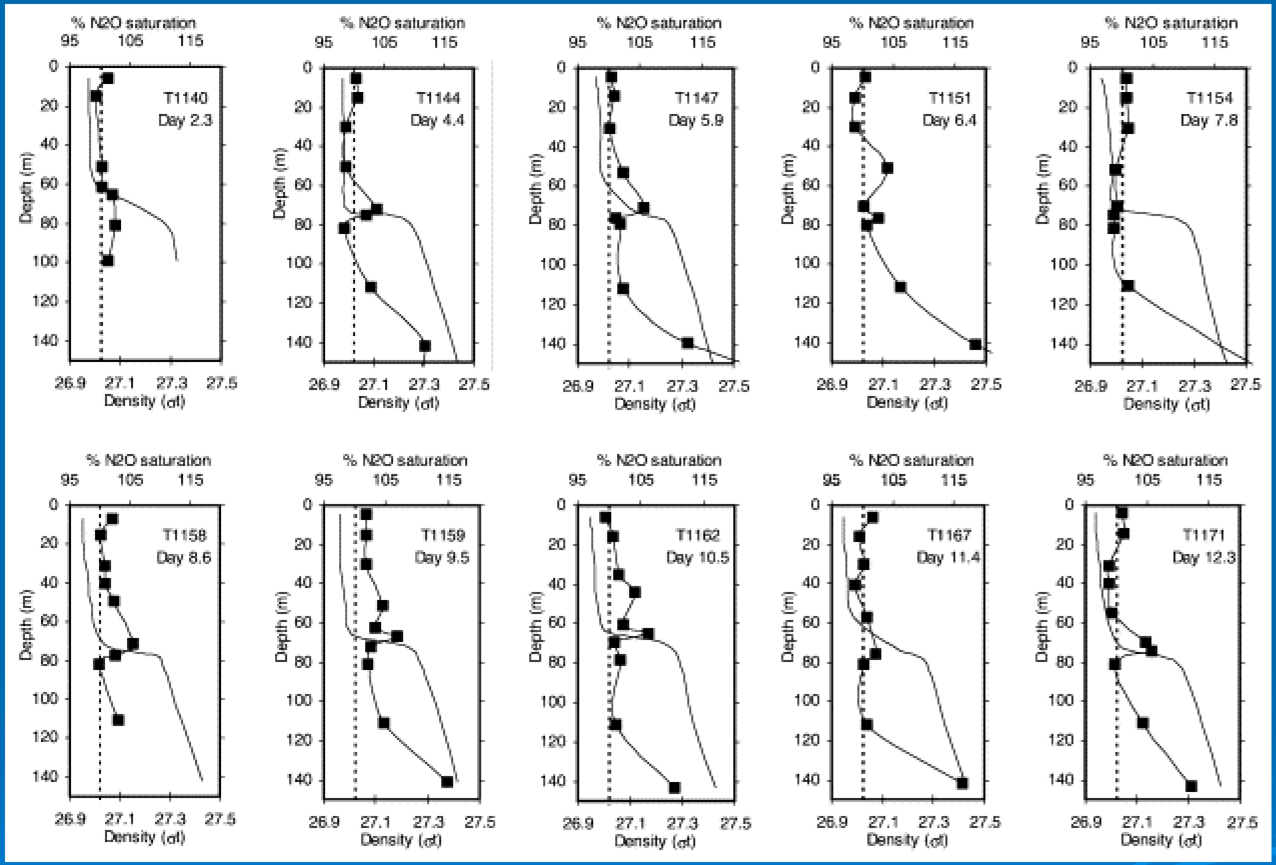


Desired result of iron fertilization is to associate more phosphate with carbon.

But this means less oxygen!

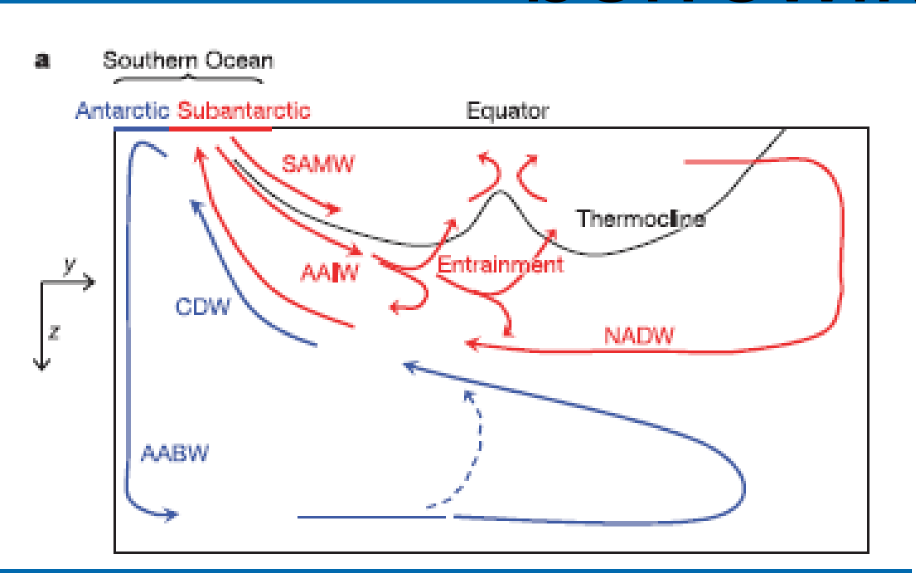
Increase in anoxic regions in deep ocean, increasing denitrification.

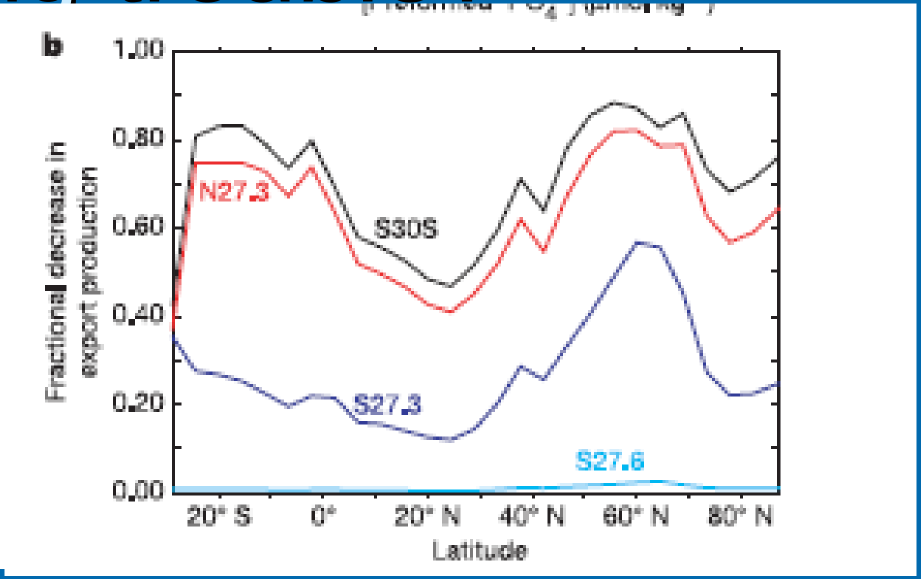
Other greenhouse gasses



Nitrous oxide production enhanced during SOIREE experiment. May offset significant fraction of carbon uptake.

Potential problems- are we borrowing trouble?

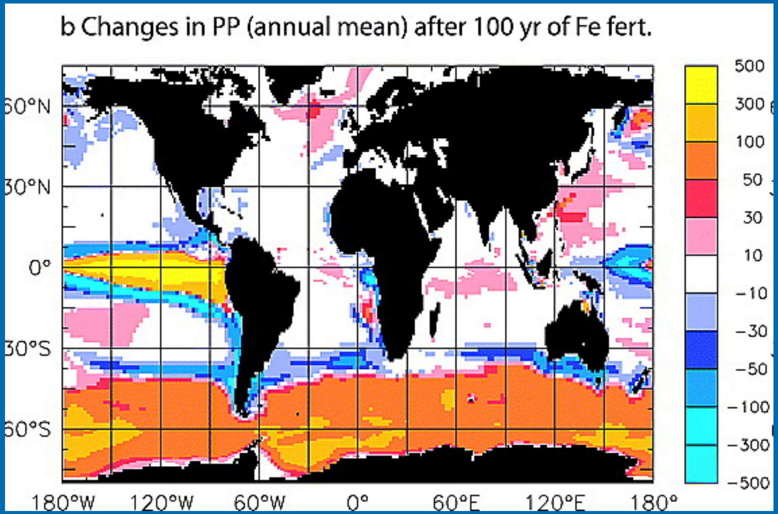


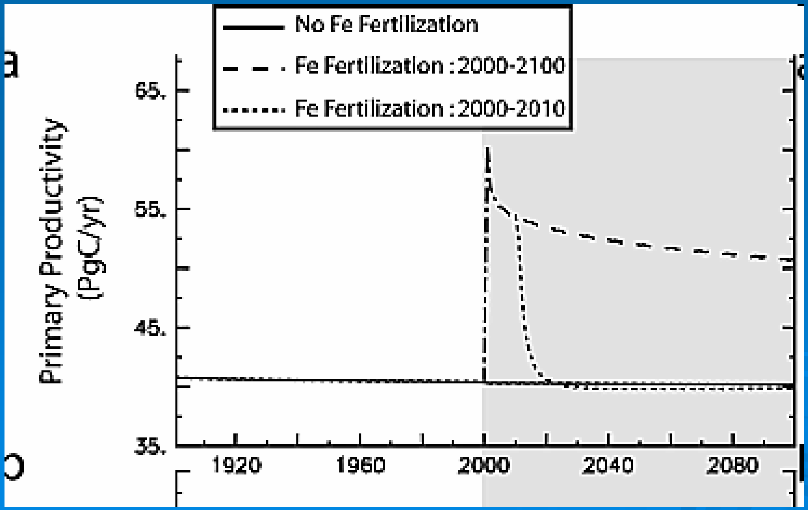


Nutrient depletion of the Subantarctic has remote consequences over many centuries.

Marinov, Gnanadesikan, Toggweiler and Sarmiento,Nature, 2006

Results from a full ecosystem model





Aumont and Bopp show regions at edge of upwelling zones losing productivity.

Atmospheric impact is 33 ppmv

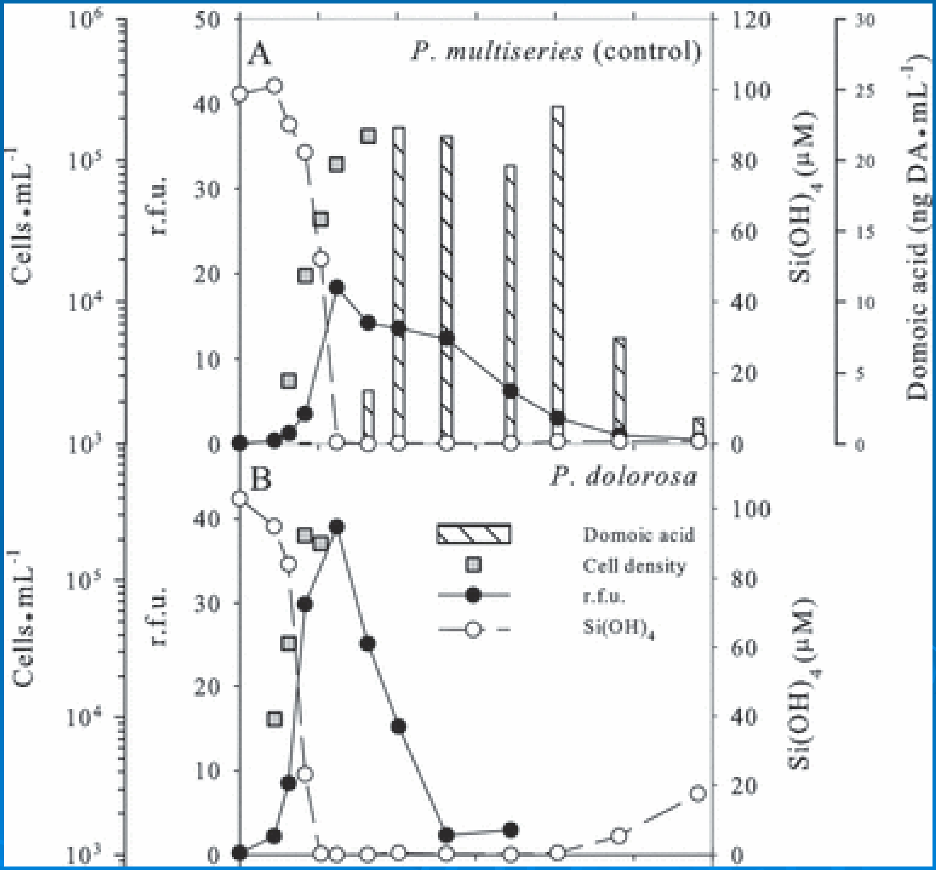
When fertilization is stopped, production is slightly lower.

Aumont and Bopp, Global Biogeochemical Cycles, 2006

Harmful algal blooms?

Some species of phytoplankton shown to be responsive to fertilization (Pseudonitzchia) are associated with marine toxin domoic acid.

Domoic acid appears to bind iron.



A. Marchetti et al., J. Phycology, 2008

How much does iron fertilization actually cost?

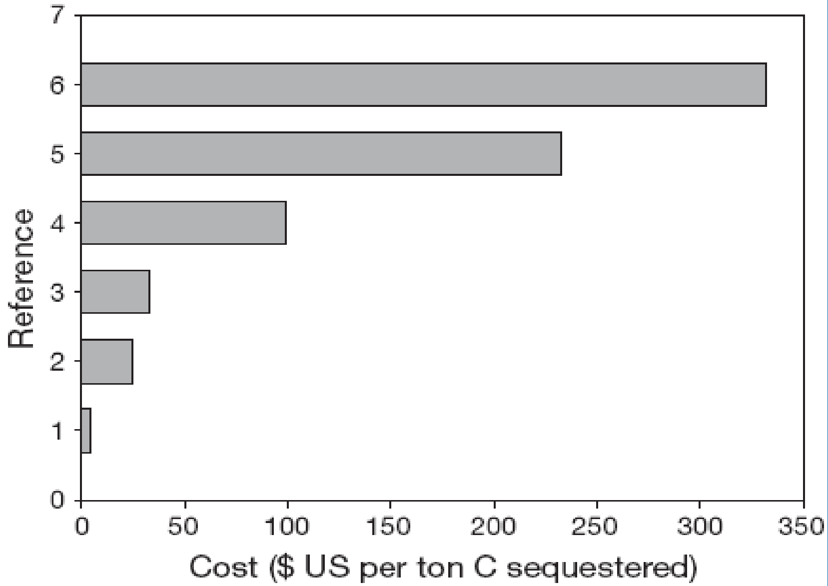
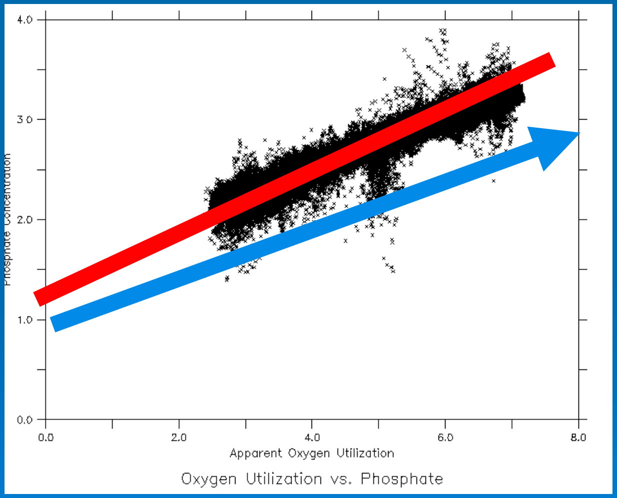


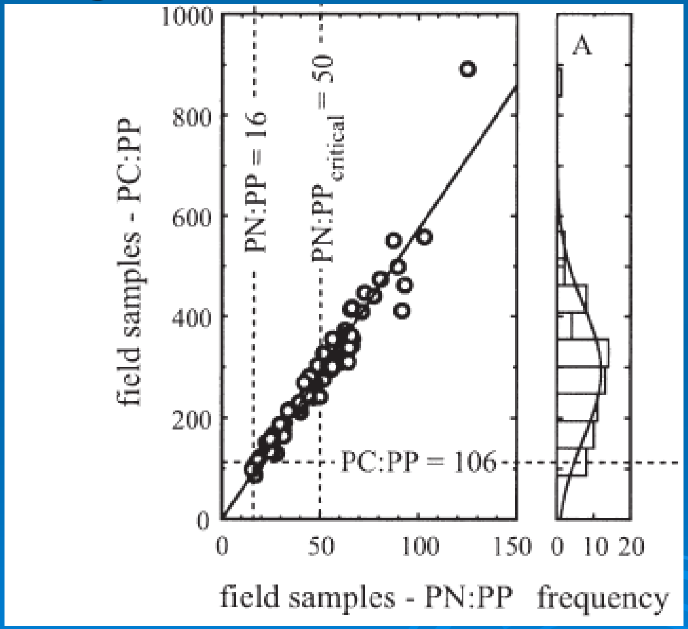
Fig. 2. Revised estimates of the cost of C sequestration by ocean iron fertilization (OIF). The estimates are based on the range of Fe:C molar ratios reported for mesoscale OIF studies and from naturally occurring blooms. These ratios are converted to a cost by simply scaling them using the Markels' Fe:C ratio of 1.37×10^{-5} as equivalent to $US 2 US ton^{-1} C sequestered. Reference 1: Markels' original estimate (http://www.wired.com/wired/archive/8.11/ecohacking_pr.html); 2: Fe:C from Southern Ocean phytoplankton (Twining et al. 2004); 3: mixed layer particulate Fe:C from the Subarctic Ecosystem Response to Iron Enrichment Study (SERIES) OIF (Boyd et al. 2004); 4: Fe:C in sinking particles from the North Atlantic Bloom Experiment (Martin et al. 1993); 5 and 6: Fe:C in sinking particles, 5: exiting the mixed layer, and 6: sinking through the permanent pycnocline (120 m depth) during the SERIES OIF, respectively (Boyd et al. 2004). These Fe:C ratios are summarized in Boyd et al. (2007), their Fig. 3. Note these estimates do not include other potential costs, such as fisheries loss levy that are listed in the main text. 1 US ton = 0.9072 t

Boyd (MEPS, 2008) shows that as one looks further and further down the chain more iron is lost, and cost appears to go up.

Alternative versions of iron fertilization

- LNLC fertilization
- Seeks to enhance nitrogen fixation



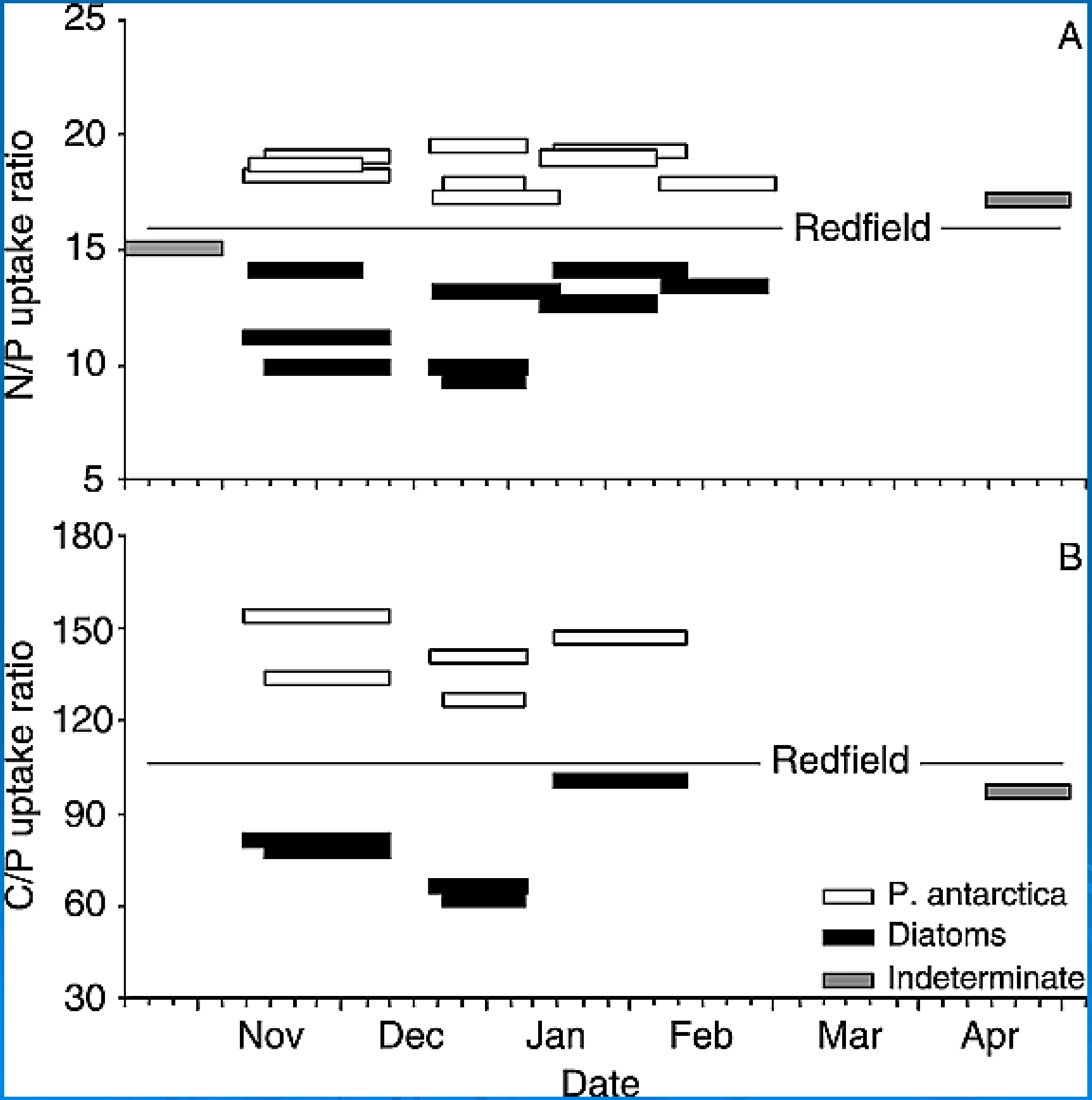


Organic matter produced by nitrogen fixation has a higher N:P, and thus C:P ratio (White et al., Limn. Oceanogr. 2006)

Iron fertilization could decrease C:P ratios

Arrigo et al., GRL, 2002

If iron fertilization leads to the replacement of diatoms in the Southern Ocean, carbon sequestration could *drop*.



Scenario	Detectability	Impact on production
Massive increase in deep export (EIFEX)	Good as regards export. Impact on preformed nutrients unclear.	Productivity drops
Iron enhances surface cycling (Aumont/Bopp)	Biggest challenge to detect marginal change.	Positive in most regions, negative at edges of productive regions
Change in C:P ratio	Easily detectable in particle traps.	Depends on interaction with low-oxygen regions, ecosystem structure

Summary

- Ocean fertilization is not a panacea- best estimates put potential atmospheric drawdown at ~33 ppmv.
- Verification is hard- requires estimating preformed carbon/nutrients, not just looking at export of organic matter.
- Ocean is three-dimensional- changing the nutrient cycle at one location changes biogeochemistry at others.

Where can I learn more?

- Marine Ecology Progress Series, v 364 open-access theme section on iron fertilization.
- Oceanus magazine, report on the Woods Hole workshop on iron fertilization.

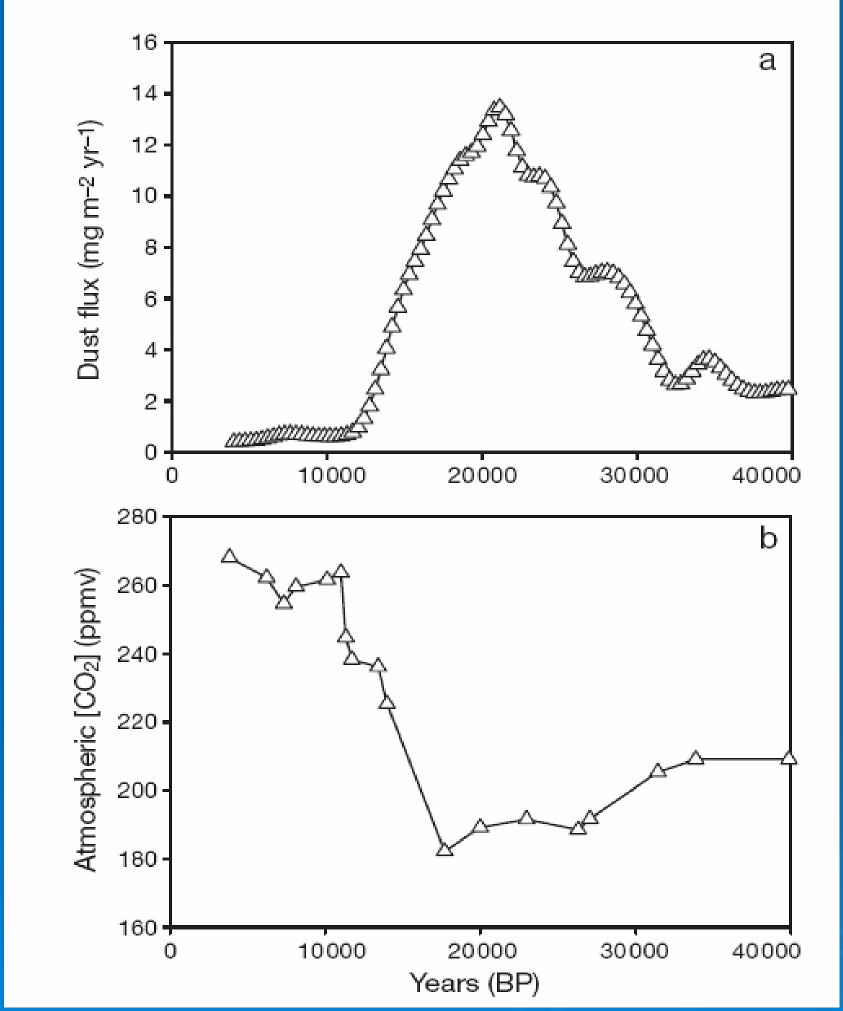
Ethics issues and iron fertilization

- Ocean as “wilderness”
  - Problematic- there are no pristine ecosystems
  - Legitimate- in that we don’t know what’s there, and that known consequences (increasing anoxia) are problematic
- “Gardening” vs. “Grazing”
  - Gardens are productive…
  - But tend to have low biodiversity.

Legal issues and ocean fertilization

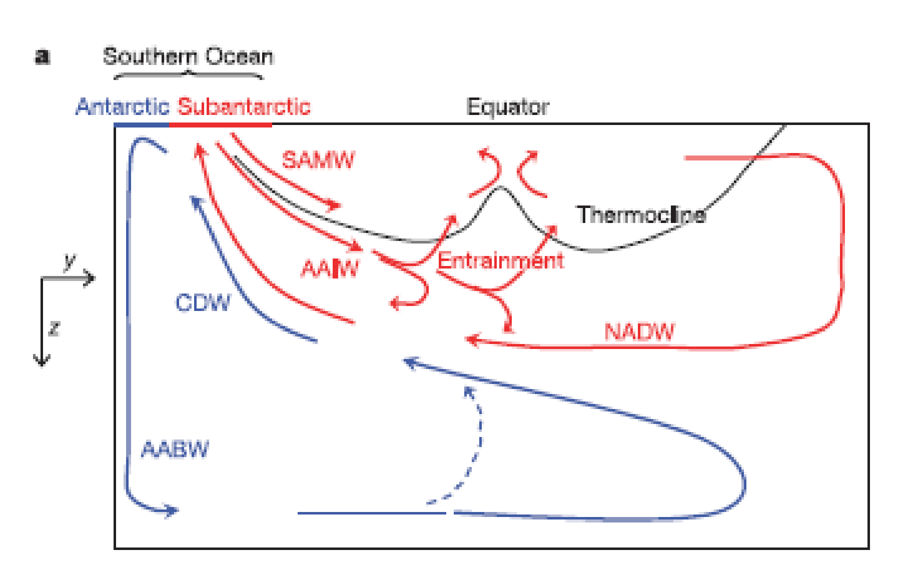
- Law of the Sea- London Dumping Convention
  - Is iron fertilization “dumping” or “emplacement”
  - Is CO_2 added by iron fertilization “dumping”?
- Clean development mechanism
  - Difficult to see how iron fertilization could comply with verifiability requirements for natural sinks
  - Would require renegotiation

Ice ages and iron fertilization



Are iron and CO2 both responding to the same climatic forcing?

Or does iron drive CO2?



From Petit et al., 1999 reproduced in Boyd, MEPS, 2008

NOAA and iron fertilization

- Chemical oceanographers eager to see scale-up to larger experiment- knowledge about iron's role in the ocean.
- Fisheries oceanographers are worried about impacts.