Ocean Carbon Sequestration: The Acid Test

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Roadmap

- Context
- Mechanisms for stimulation of ocean uptake
  - Uptake of residual nitrate
  - Enhance nitrogen fixation (residual phosphate)
  - Direct addition of nitrogen
  - Ocean pumping
- Potential consequences
- Verification
- Choices

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Disclosures

- Director of the Wrigley Institute for Environmental Studies (1996-2008)
- Collaborations with various environmental organizations (1976-2008)
- Conversations with Commercial Entities
  - Planktos (pre-2001)
  - Climos (2006-2007)
- Proteus Environmental Technologies LLC (Co-founder – Greentech incubator with investments in biofuels, waste-to-energy, clean water, sustainable seafood and carbon markets, potential future investor in carbon sequestration technologies)

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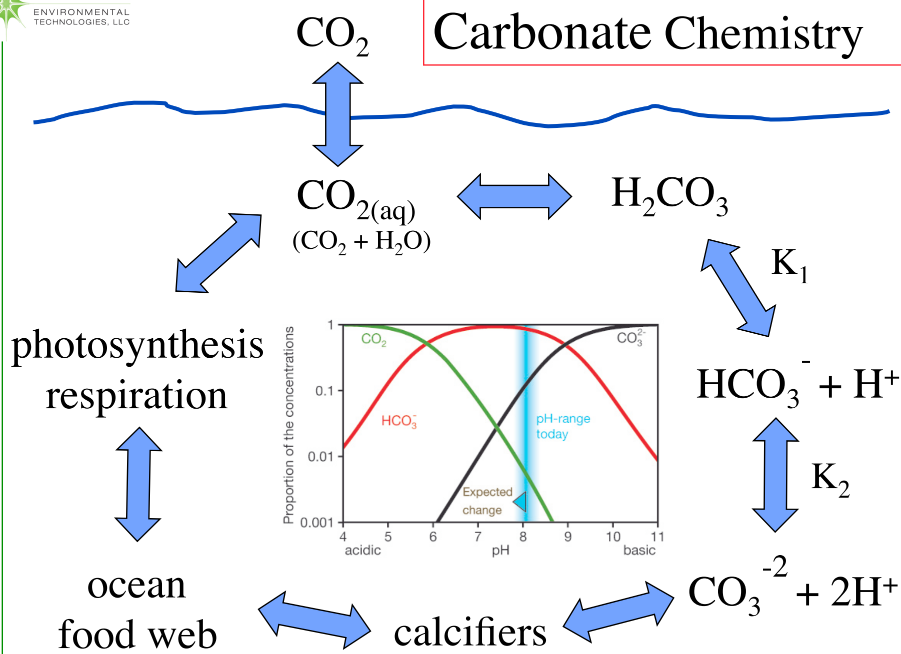
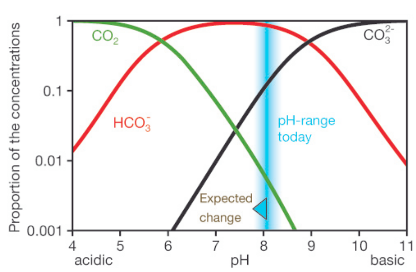
Reasons for Concern

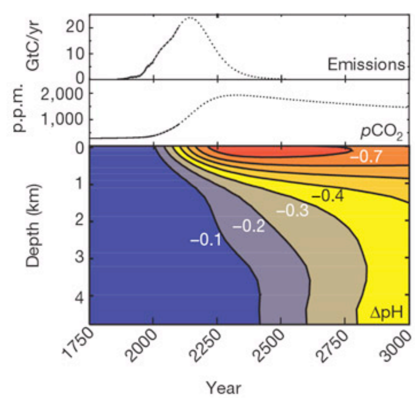
- Obvious climate change impacts on land, oceans and economy
- Specific direct effects of carbon dioxide on oceans
  - Carbonate system
  - Ocean productivity

Carbonate Chemistry



Ocean Acidification





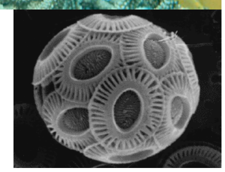
Calderia & Wickett, Nature [2003]

Possible Biological Impacts

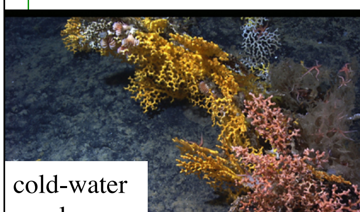
- Shell forming plants & animals
- Habitat loss (reefs)
- Less food for predators
- Possible effects on larvae

warm-water corals

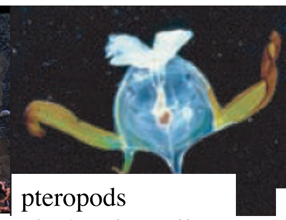
lobsters, crabs



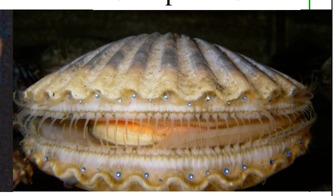
some plankton



cold-water corals

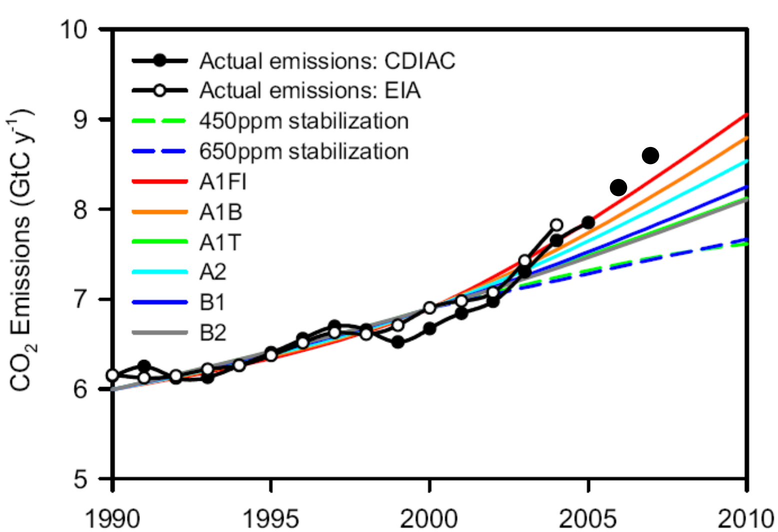


pteropods planktonic snails



scallops, clams, oysters

Emissions are Rising Faster than Expected

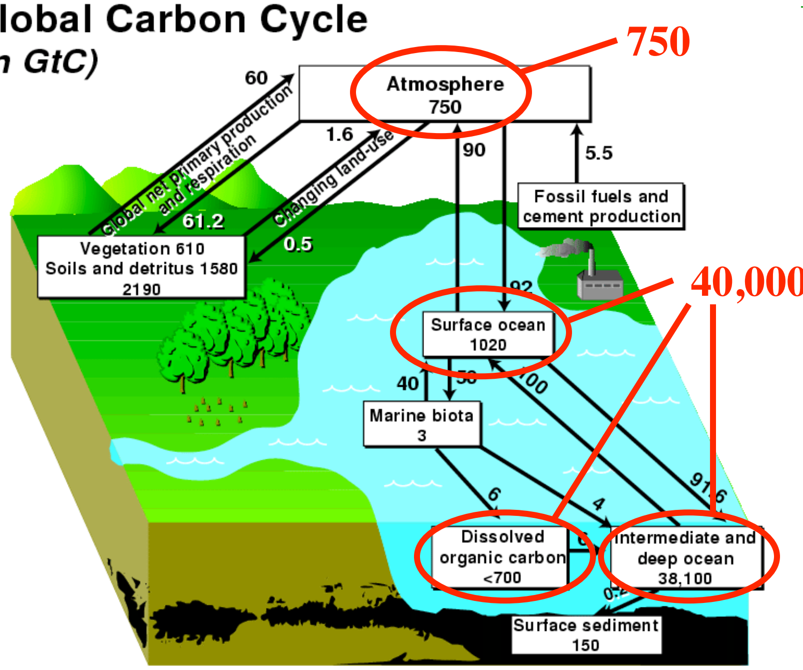


What Biological Processes Can Affect Air-Sea Partitioning of Carbon Dioxide?

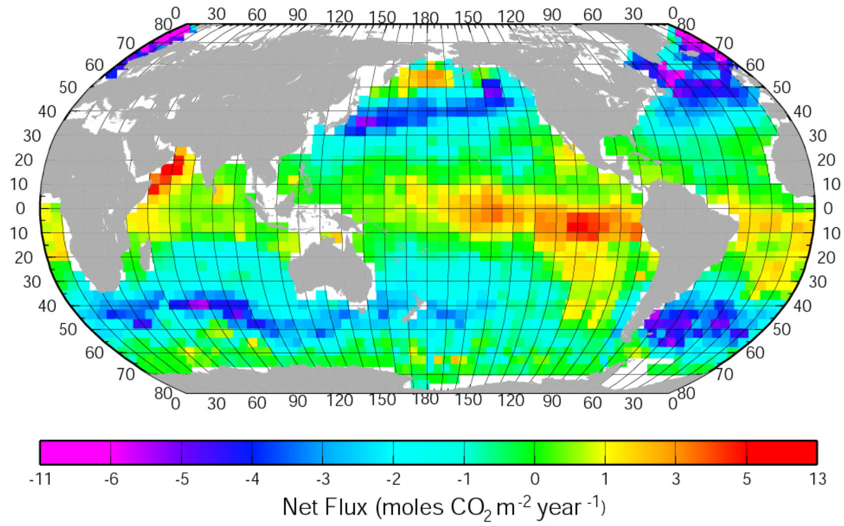
1. Incomplete nutrient utilization
2. Particulate inorganic carbon:organic carbon ratio
3. Changes in total stock of reactive nitrogen (nitrogen fixation:Denitrification balance, direct addition of reactive nitrogen)
4. Changes in remineralization length-scales and C:N:P of export

Global Carbon Cycle

(in GtC)

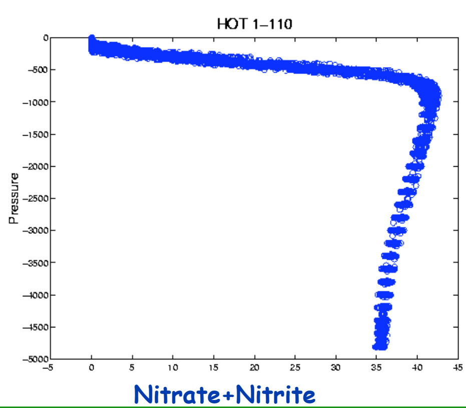


Net Annual CO_2 Flux



from Takahashi *et al*., 2002

Ocean Biology is Limited by the Supply of Nutrients



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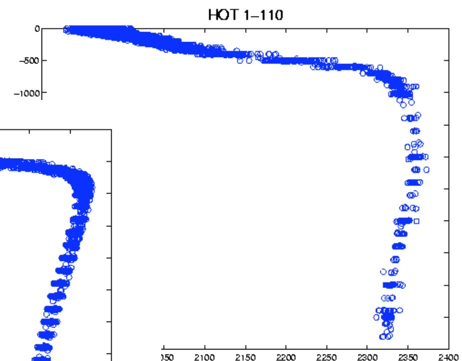
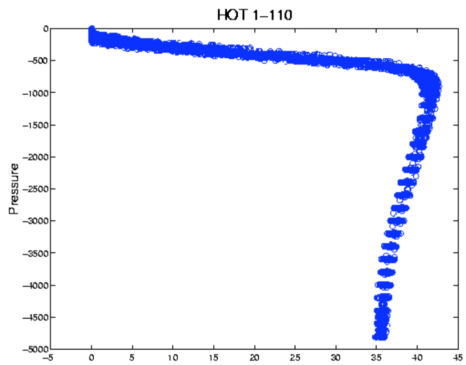
Uptake of Nutrients Maintains a Vertical Gradient in Dissolved Inorganic Carbon



Dissolved Inorganic Carbon



Nitrate+Nitrite

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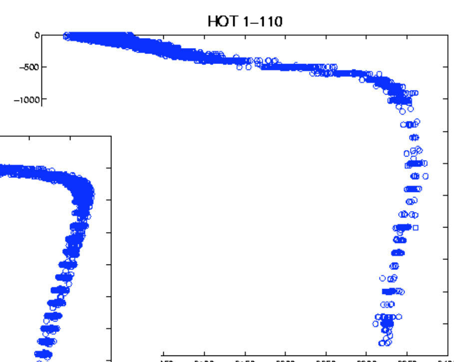
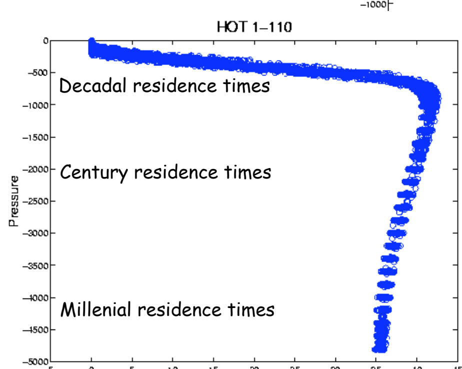
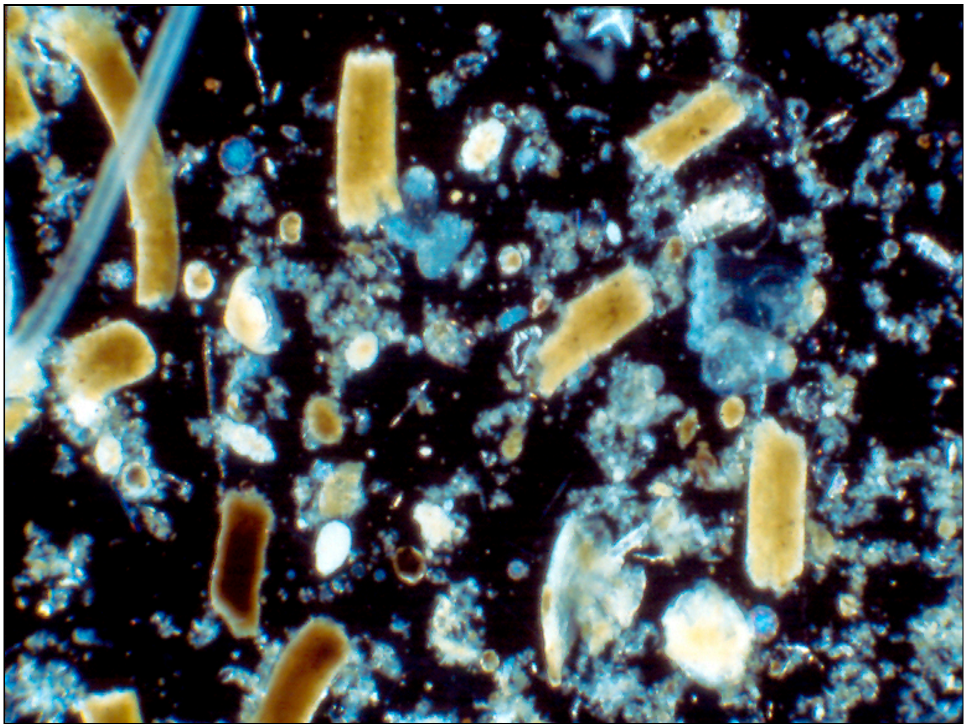
Nutrients “Sink” out of the Surface and are “Stored” in the Deep Sea (Deeper = Longer)



Dissolved Inorganic Carbon



Nitrate+Nitrite



Mechanisms for stimulation of net ocean uptake of CO_2

- Uptake of residual nitrate
- Enhance nitrogen fixation (residual phosphate)
- Direct addition of nitrogen
- Ocean pumping

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All of these are Time-Shifting

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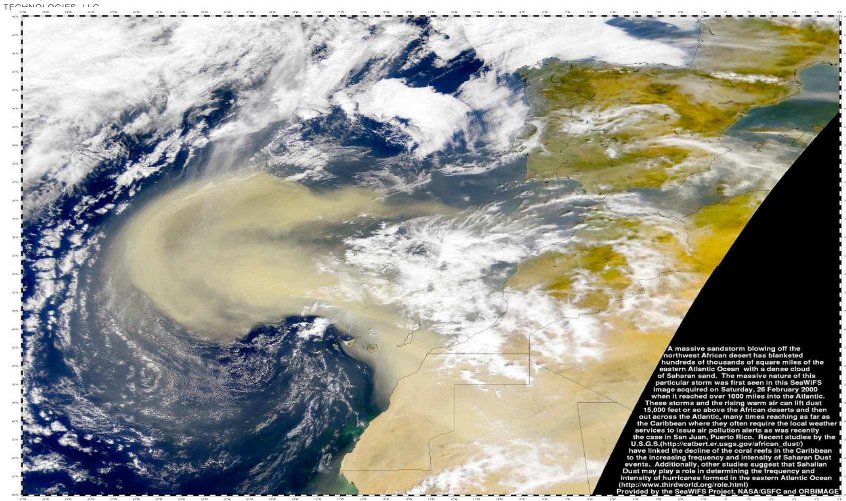

Natural Analog
For most of the oligotrophic ocean
Fe source is dust

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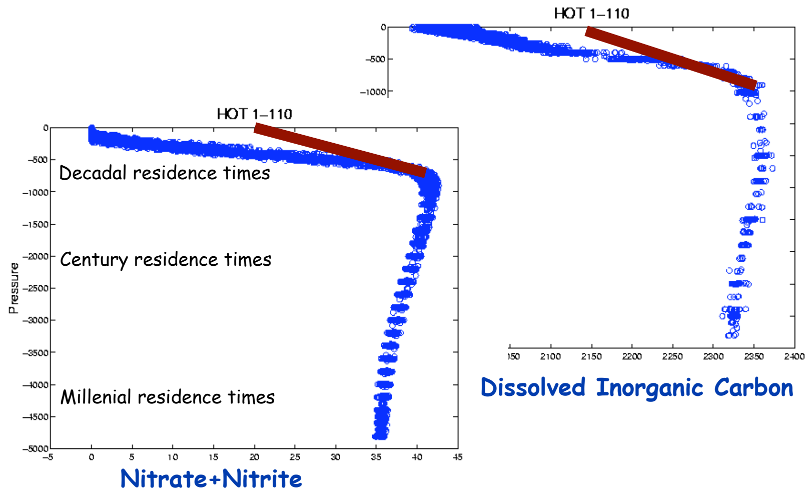
1. Incomplete Nutrient Utilization in the Surface Waters (HNLC)



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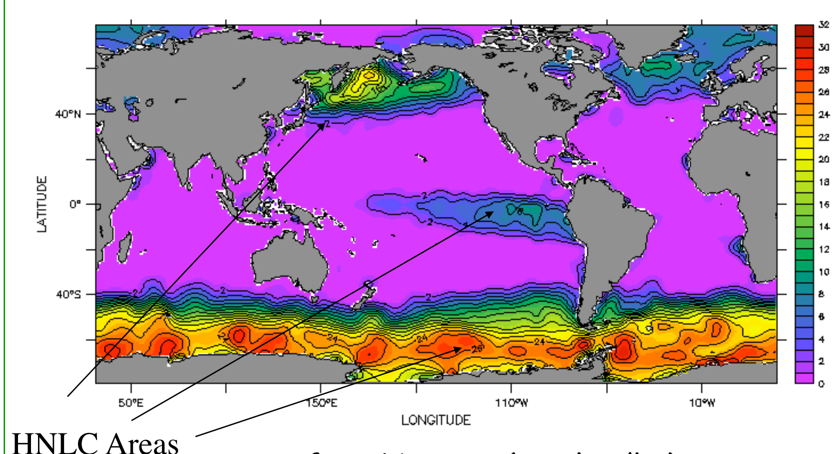
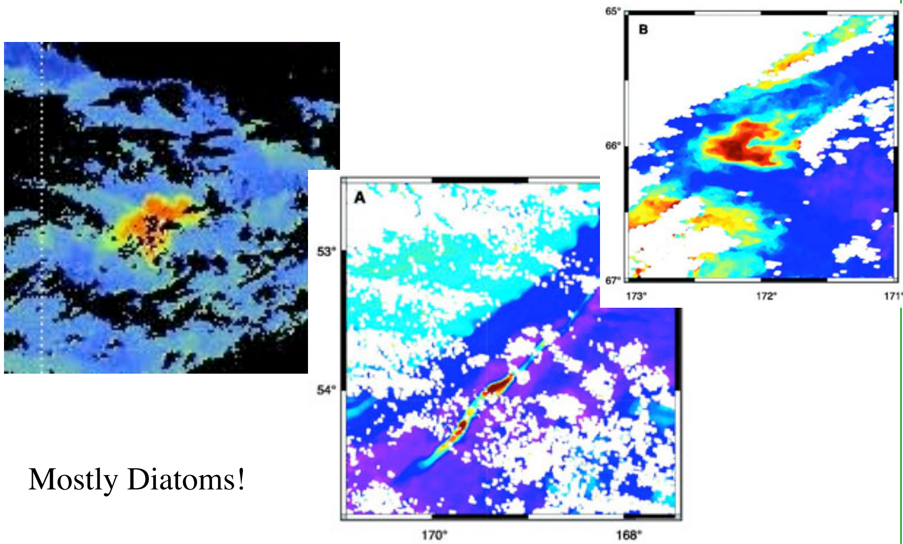
Most of the Ocean Shows Near-Complete Nutrient Utilization

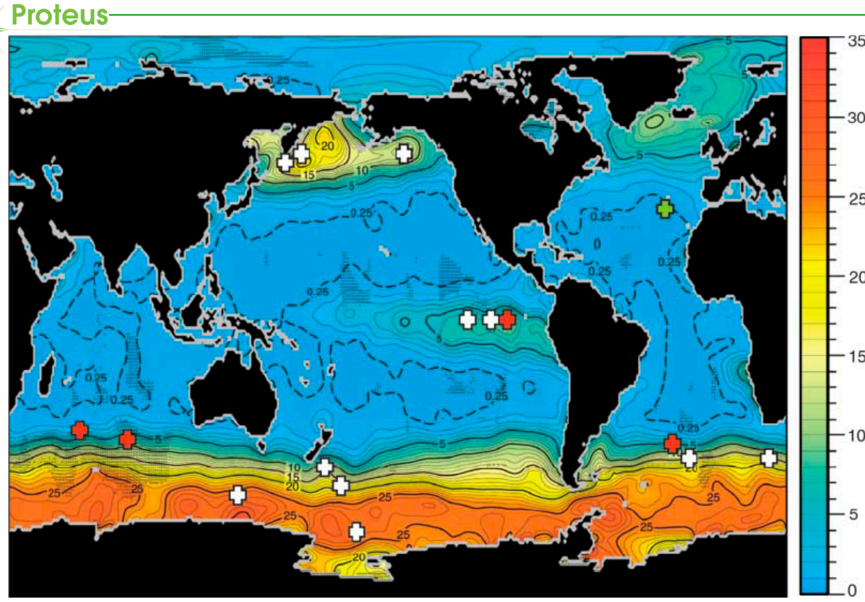


Surface Nitrate (μmoles/kg)

Fe induced blooms



Mostly Diatoms!



Boyd et al., 2007

Property	IronEX I (6)	IronEX II (30)	SOIREE (49)	EisenEx (56)	SEEDS I (57)	SOFEX-S (54, 58)	SOFEX-N (58)	EIFEX (46)	SERIES (17)	SEEDS II (59)	SAGE (59)	FeeP (59)
Fe added (kg)	450	450	1750	2350	350	1300	1700	2820	490	480	1100	1840
Temperature (°C)	23	25	2	3 to 4	11	−1	5	4 to 5	13	9 to 12	11.8	21
Season	Fall	Summer	Summer	Spring	Summer	Summer	Summer	Summer	Summer	Summer	Fall	Spring
Light climate (μmol quanta m^{-2} s^{-1})	254 (max) to 230 (min)	216 to 108	59 to 33	82 to 40	178 to 39	103 to 62	125 to 74		173 to 73		59 to 52	
Dilution rate (day^{-1})	0.27	0.18	0.07	0.04 to 0.43	0.05	0.08	0.1		0.07 to 0.16			0.4
Chlorophyll, $t = 0$ (mg m^{-3})	0.2	0.2	0.2	0.5	0.9	0.2	0.3	0.6	0.4	0.8	0.6	0.04
Chlorophyll, maximum (mg m^{-3})	0.6	3.3	2.3	2.8	23.0	2.5	2.4	3.0	5.5	2.4	1.3	0.07
MLD (m)	35	40*	65*	80*	13	35	45	100	30*	30	70*	30*
Bloom phase (duration, days)	Evolving (5) subducted	Decline (17)	Evolving (13)	Evolving (21)	Evolving (10)	Evolving (28)	Evolving (27) subducted	Partial decline, evolving	Decline (25)	Evolving (25)	No bloom (17)	No bloom (7)
delDIC	6	26	17	14	58	21	13		36		nc	<1
δDMS (μmol m^{-3})	0.8	1.8	2.9	1.3, then to 0†	nc	nc	Increased		8.5, then to −5.7†	nc	nc	nc
Dominant phytoplankton	Mixed	Diatom	Diatom	Diatom	Diatom	Diatom	Mixed	Diatom	Diatom	Mixed	Mixed	*Cyanobacteria Prochlorococcus*
Export	nc	increase	nc	nc	nc	Increase	Increase§	Increase	Increase	nc	nc	
Mesozooplankton stocks	Increase‡	Increase	nc	nc	nc	nc	nc	Increase	Increase	Increase	nc	nc
Primary production (max/min ratio)	4	6	9	4	4	6	10	2	10		2	1.7

*Changes in MLD were observed during the study; the maximum MLD is shown (for initial MLD, see table S1). †An initial increase in DMS concentration followed by a decline by the end of the study. ‡Based on anecdotal evidence. §Increased export was mainly associated with a subduction event.

Boyd et al., 2007

HNLC Regions

- Trace nutrient limitation (Fe), C:Fe ~ 1,000-3,000
- Reduce HNLC area worldwide - 15-100 ppm reduction in atmospheric CO_2
- Small blooms are hard to follow – need larger and longer experiments.
- Reintroduction of carbon dioxide and nutrients to the surface is the big open question – how long is the carbon stored?

How do we store the carbon for more than 20 or 50 or 100 years?

Site Selection: Need the "right" HNLC area

- 100 year horizon is shallow
- Export from blooms is large and goes deep
- Nutrient uptake would "not" happen without additional iron
- Surface and subsurface conditions conducive to minimal negative environmental impacts

Site Evaluation

Southern Ocean

+ Lots of nitrate, very predictable blooms on Fe addition
- Mixing makes 100 yr horizon deep

Equatorial Pacific

+ Modest nitrate, modest predictability
- Upwelling zone, nitrate will be used eventually anyway, sits over denitrification zone

North Pacific

+ Modest nitrate, documented deep fluxes, 100 yr horizon is relatively shallow
- Fewer Fe experiments in areas with documented deep fluxes

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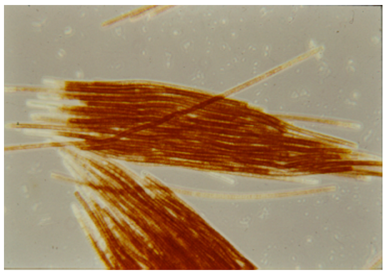
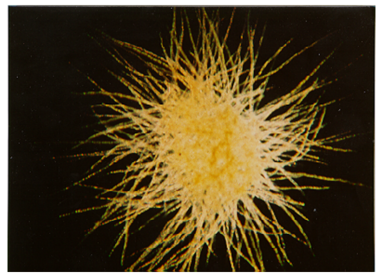
Trichodesmium spp.

Best Known Planktonic Diazotroph





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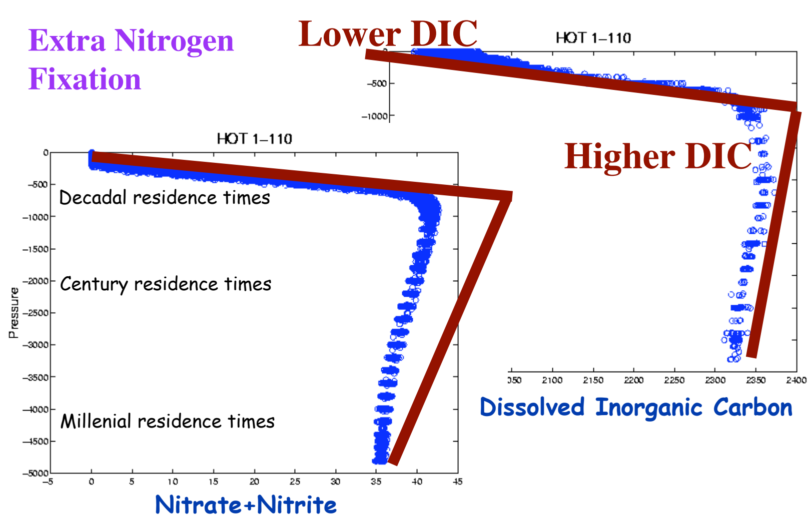
2. Changes in Nitrogen Fixation - Denitrification Balance



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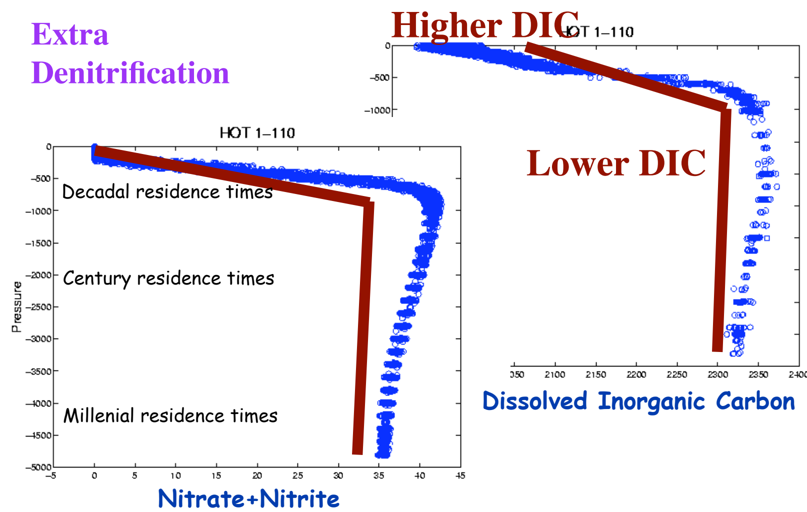

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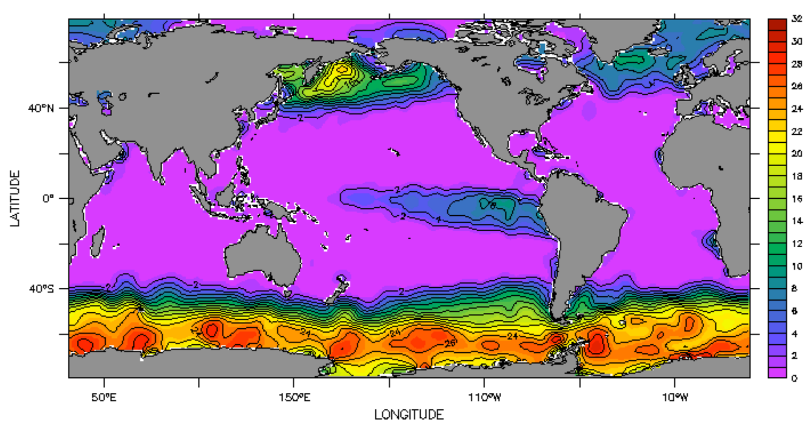
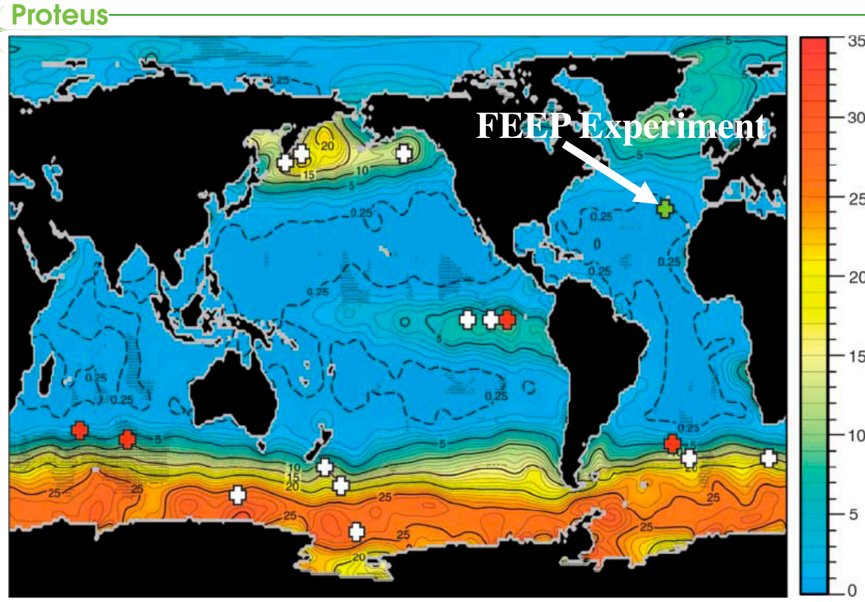
Most of the ocean shows near-complete nutrient utilization



Surface Nitrate (μmoles/kg)

Fe Addition and Nitrogen Fixation - Existing Data

- FeeP - Fe and SRP addition in NE Atl.
- Amazon Plume (High Fe, PO4)
- Bottle Incubations (Fe, SRP, dust)
- HOT data - recurring summer signal (Karl)

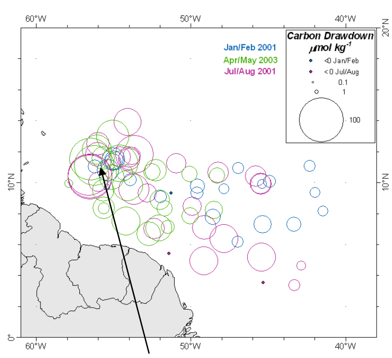


Boyd et al., 2007

FeeP (Rees, et al., 2007)

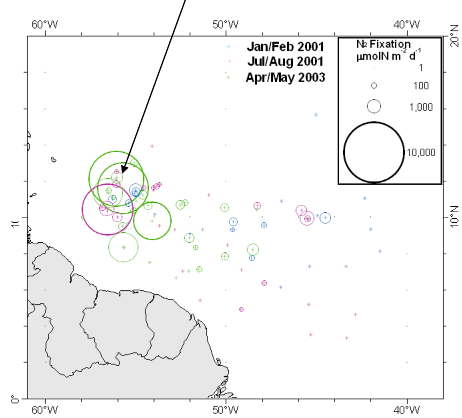
- Added Fe and PO4 to a low Fe and P area of NE Atlantic
  - 25 km^2 patch of Fe only
  - 25 km^2 patch with Fe and P
- Followed for about 3 weeks
- Fe+P patch, *Trichodesmium* increases
- N fixation rates increased 6 fold and 4.5 fold respectively

Amazon Plume Data (Cooley et al)



Highest carbon
Drawdown in center
Of N-fixation blooms

N-fixation blooms in
Amazon plume



Conclusions From Previous Research on NFix

- Reasonable likelihood that nitrogen fixation is influenced by availability of Fe in the North Pacific and that addition of Fe will stimulate growth of diazotrophs (variable N:P)
- Growth of diazotrophs can lead to DIC drawdown

Sequestration Time-scale

- Differs from HNLC areas
- Biological re-use should keep carbon and new nitrate below the surface for extended periods

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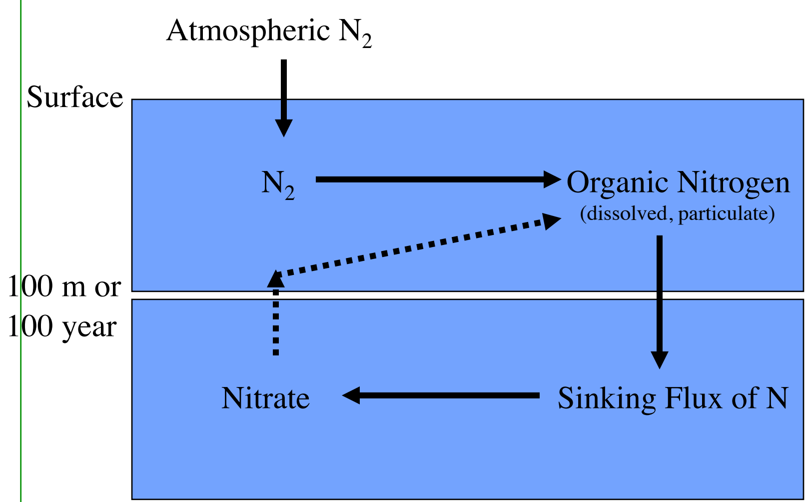
How to Understand and Measure the Effect: Create Mass Balance for Upper Ocean



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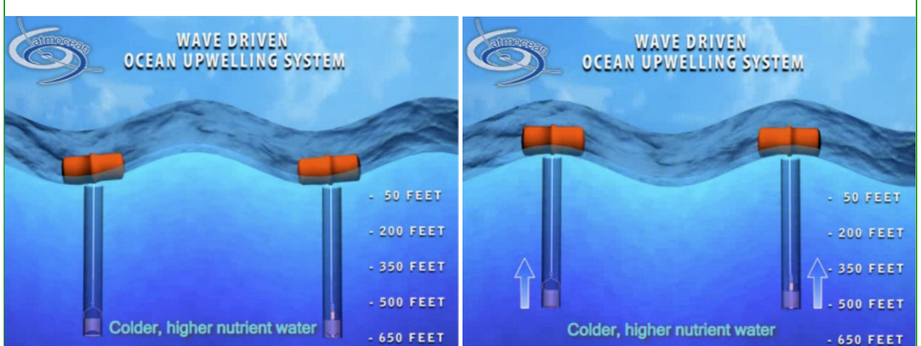
Sequestration Time-scale

- Biological re-use should keep carbon and new nitrate below the surface for extended periods
- Carbon storage until:
  - Upwelled in HNLC area and extra nitrate is left un-used (if that happens)
  - Passes through denitrification zone, followed by upwelling to the surface without the extra nitrate
- Both of these time-scales can be centuries when the correct location is chosen

Other Proposed Mechanisms for Ocean Sequestration

- Direct Addition of Nitrate, Ammonia or Urea (Ocean Nourishment Corporation)
  – Should be directly analogous to nitrogen fixation on global scale
  – Enormously expensive unless ….
- Ocean Pumping (Atmocean Corporation and others)

Ocean Pumping



Who Knows?
- Stimulate nitrogen fixation
- Increase remineralization length-scale

Environmental Impact Issues

- Other Trace Greenhouse Gases
  - N_2O, methane, DMS
- Harmful algae or other ecosystem distortions
- Oxygen anomalies
- Ocean Acidification

Other Trace Gases

- Nitrous Oxide, Methane
- Both potent greenhouse gases
- Handled on market side as “leakage”
- DMS – other radiative impacts
- Critical to measure over duration of experiment and beyond
- Natural experiments can give longer perspective

Harmful Algae and Ecosystem Shifts

- HABs may depend on definition
- Targeted Assays for ones you expect
- Exploratory Research for ones you don't

- Ecosystem shifts inevitable
- Genomic Approaches to structure and function

Oxygen Depletion

- At one level, a given if it works
- At another level, a measureable and manageable impact

Watch this one – anyone who cites this issue is implying that Fe fertilization works!

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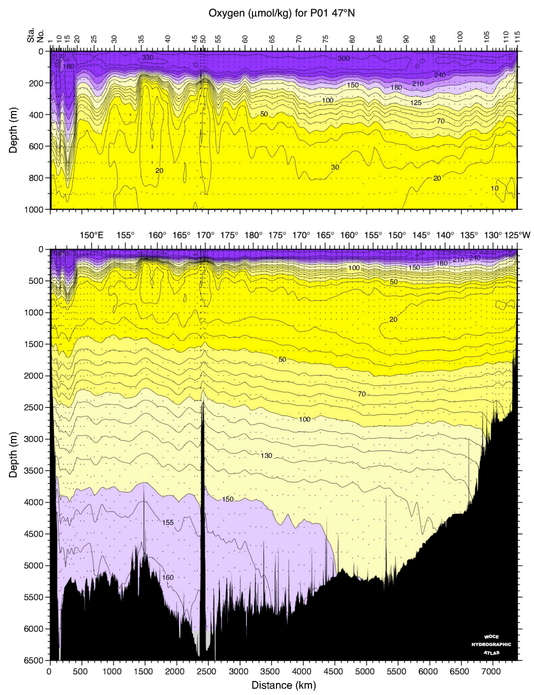

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Sample Calculations

- Assume 1.25 moles C/m^2/bloom
- What happens if we redistribute this from 500-1500 m through remineralization?
- Assume O_2:C = 1.38:1
- Assume deep O_2 = 20 μmoles/kg
- Net drop in oxygen = 1.7 μmoles/kg

Near limits of detection before mixing

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Ocean Acidification

- Already happening at surface
- Deep transport effects pattern
  - Reduces surface acidification
  - Increases deep acidification
- Deep acidification spread over larger depth range – should slow its effects

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Verification Challenge

- Need to create and demonstrate a minimum set of measures to convince science community and markets
- Measure fluxes through depth horizons
- Measure DIC drawdown in euphotic zone and DIC increase at depth
- Large enough patches to “see” the signal
- Equally tied to markets as to science

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Finally - Choices

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What is the Role of Markets?

- Evil force?
- Enormous opportunity?
- Barrier to progress?
- The best mechanism for solutions?

- A little of each?
- Something else entirely?

What is the Role of Science?

An International Ocean Science Organization says:

- "… the current scientific evidence indicates that this will not significantly increase carbon transfer into the deep ocean or lower atmospheric CO2."
- "… there may be negative impacts of iron fertilization including dissolved oxygen depletion…"
- "… the judgement of the XXXXX is that ocean fertilisation will be ineffective and potentially deleterious, and should not be used as a strategy for offsetting CO2 emissions…"

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- **What is the role of science?**
  - Prejudge?
  - Advise?
  - Define Problems?
  - Find Solutions?
  - Discover?
  - Advocate?

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The Quandary

- How bad is global warming?
- How bad is ocean acidification?
- How soon do we see the longer-term solutions?
- Do we need to buy time?
- How do we balance uncertain impacts of one problem against both known and uncertain problems with one part of the solution?

In my opinion, this is the great challenge of this generation.

We must get this right!

Thank you.