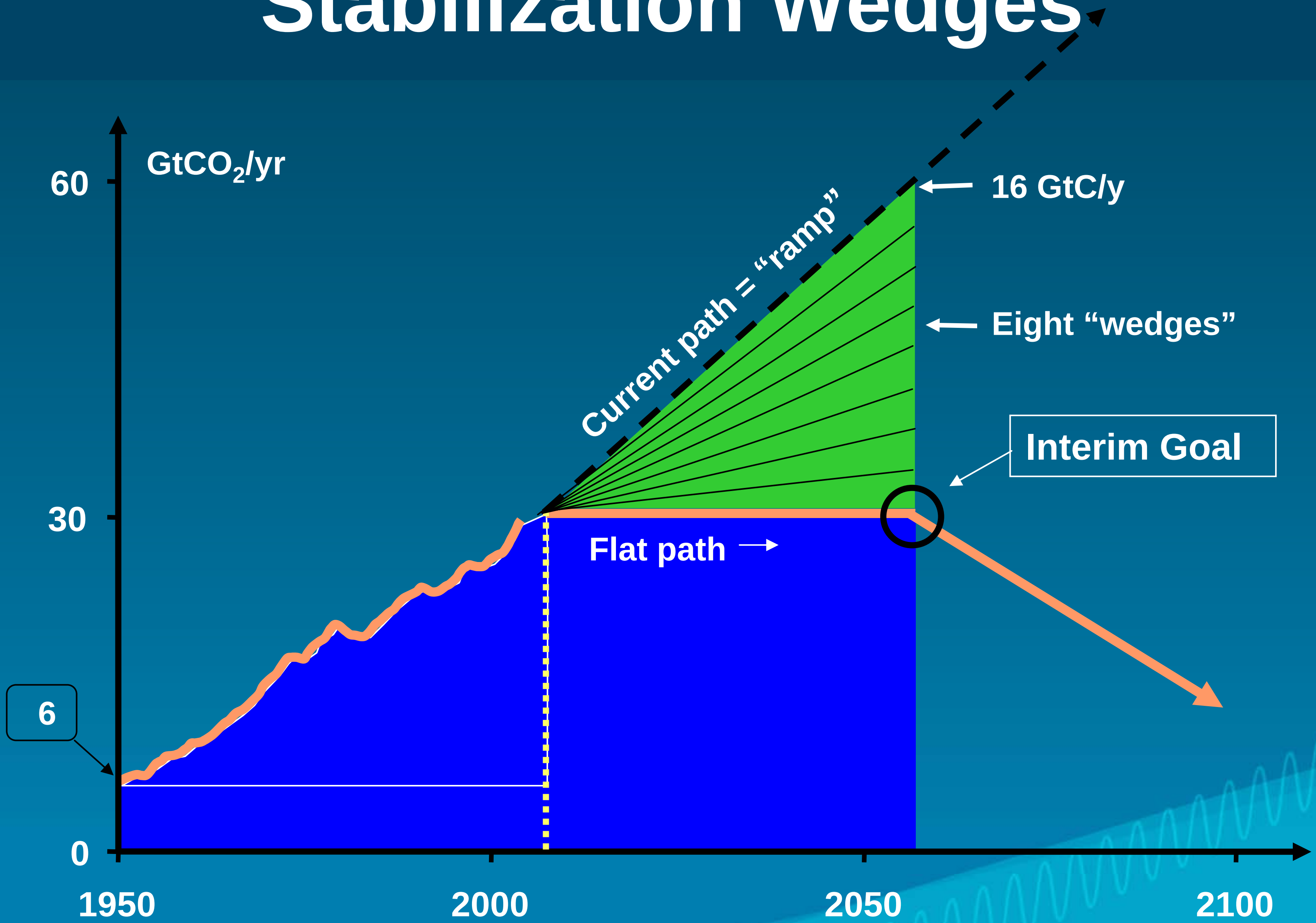
Improving the Efficiency of the Ocean's Biological Carbon Pump

David M. Karl
University of Hawaii
and friends

Stabilization Wedges



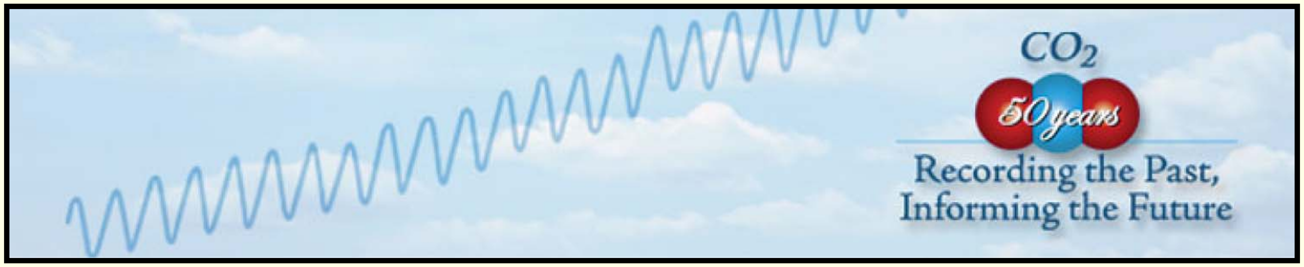
R. Socolow, 28 Nov 2007

Exploring Ocean Iron Fertilization: the scientific, economic, legal and political basis

Symposium held at Woods Hole Oceanographic Institution
26-27 September 2007
K. Buesseler, S. Doney, H. Kite-Powell, co-organizers
http://www.whoi.edu/page.do?pid=14618

***Oceanus* article by Hugh Powell**
http://www.whoi.edu/oceanus

“Moving ahead with uncertainty”



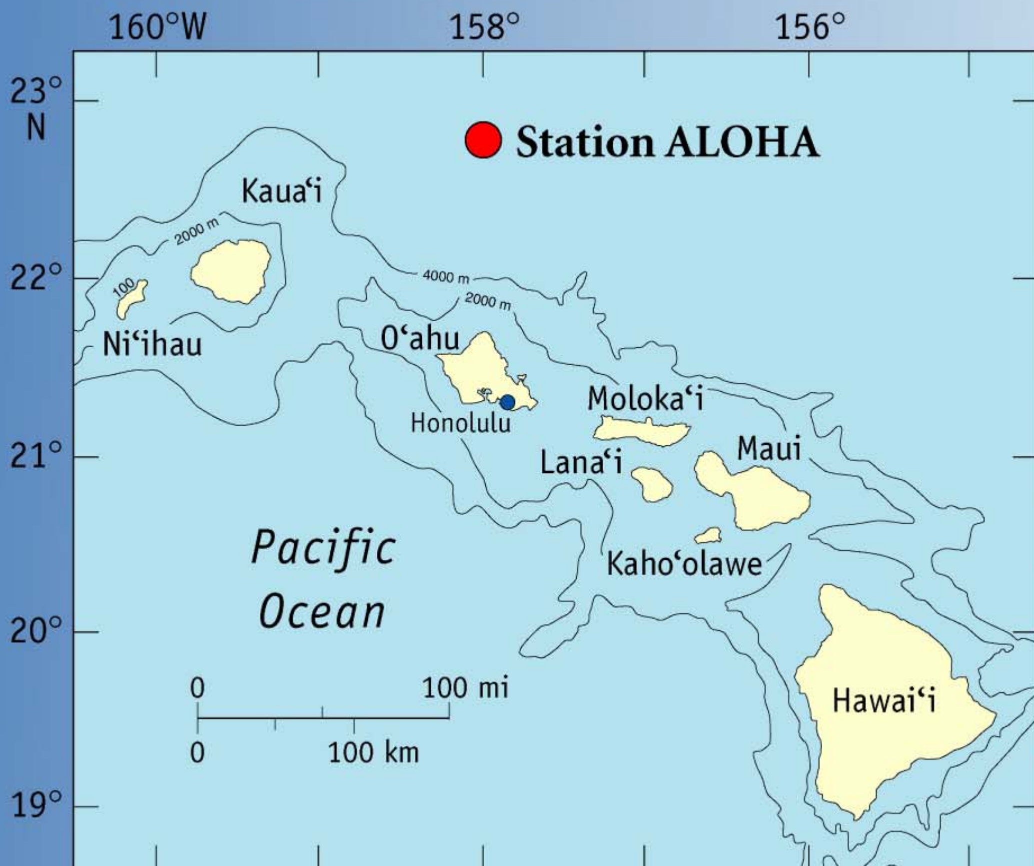
ACKNOWLEDGEMENTS

- Melinda Marquis / Annie Thomson and all organizing and planning committee persons
- My “advisors” for this talk:

  Phil Boyd, Ken Buesseler, John Cullen, Scott Doney, Ken Johnson, Ricardo Letelier, Anthony Michaels

OUTLINE

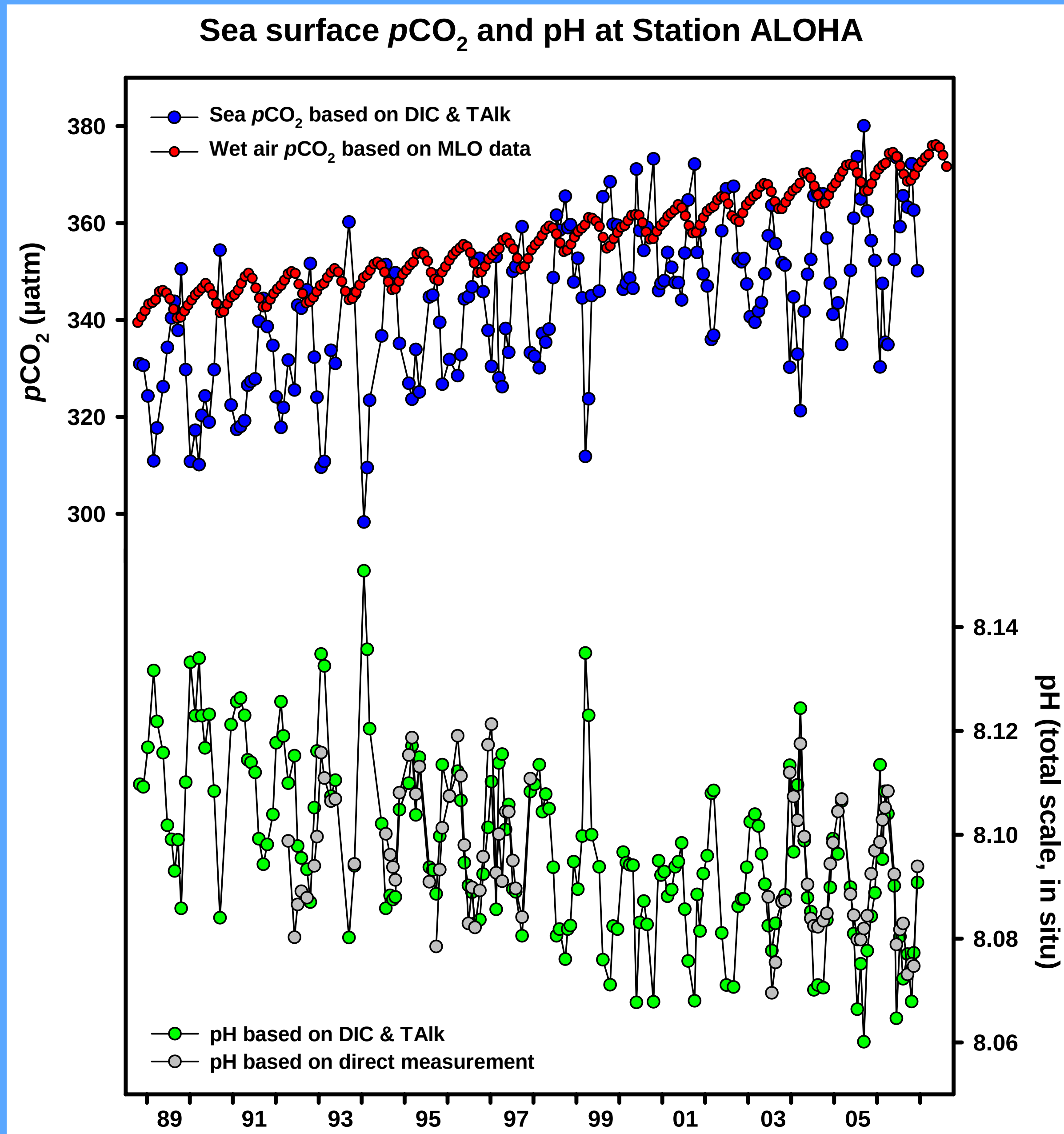
- Station ALOHA ***(Mauna Loa of the Sea)***
- Ocean’s Biological Carbon Pump
- Ocean Fertilization: Design, Implementation and Outcomes ***(expected and unexpected)***
- The Future



Hawai'i Ocean Time-series (HOT)

Data availability:
http://hahana.soest.hawaii.edu

Contact:
D. Karl (dkarl@soest.hawaii.edu)



Sea surface pCO2 and pH at Station ALOHA
Sea pCO2 based on DIC & TAlk
Wet air pCO2 based on MLO data
pCO2 (µatm)
380
360
340
320
300
pH (total scale, in situ)
8.14
8.12
8.10
8.08
8.06
pH based on DIC & TAlk
pH based on direct measurement
89
91
93
95
97
99
01
03
05

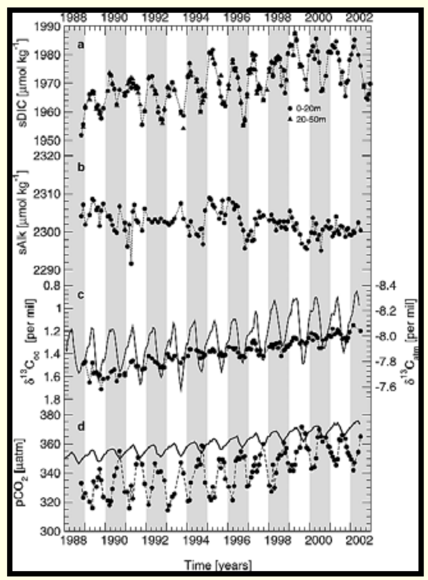
Seasonal and long-term dynamics of the upper ocean carbon cycle at Station ALOHA near Hawaii

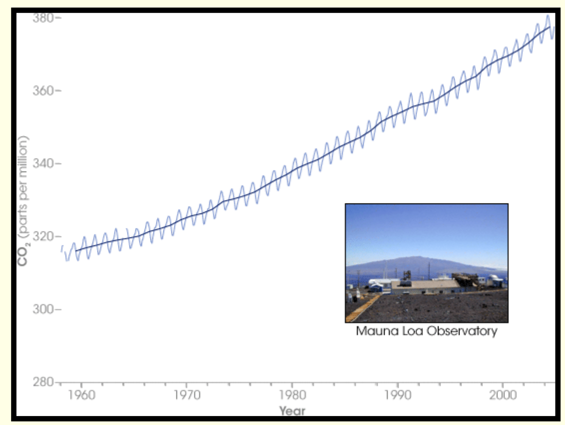
Charles D. Keeling
Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA

Holger Brix
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA

Nicolas Gruber
Institute of Geophysics and Planetary Physics and Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA

Received 23 January 2004; revised 27 May 2004; accepted 2 July 2004; published 15 October 2004.

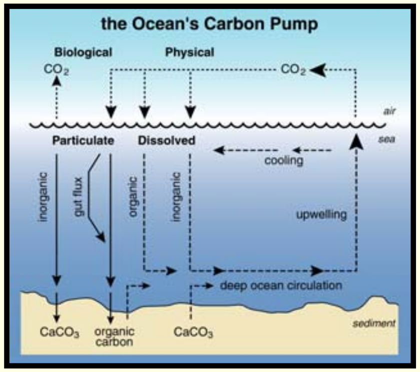


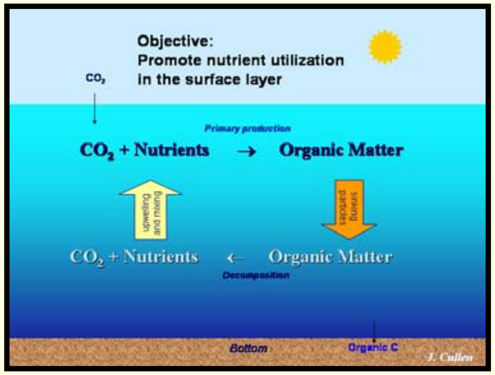


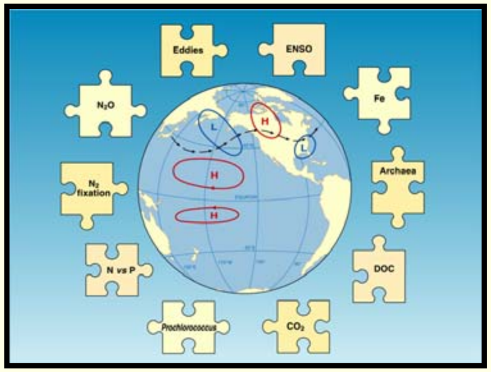
Keeling et al. 2004, *Global Biogeochemical Cycles*, vol. 18

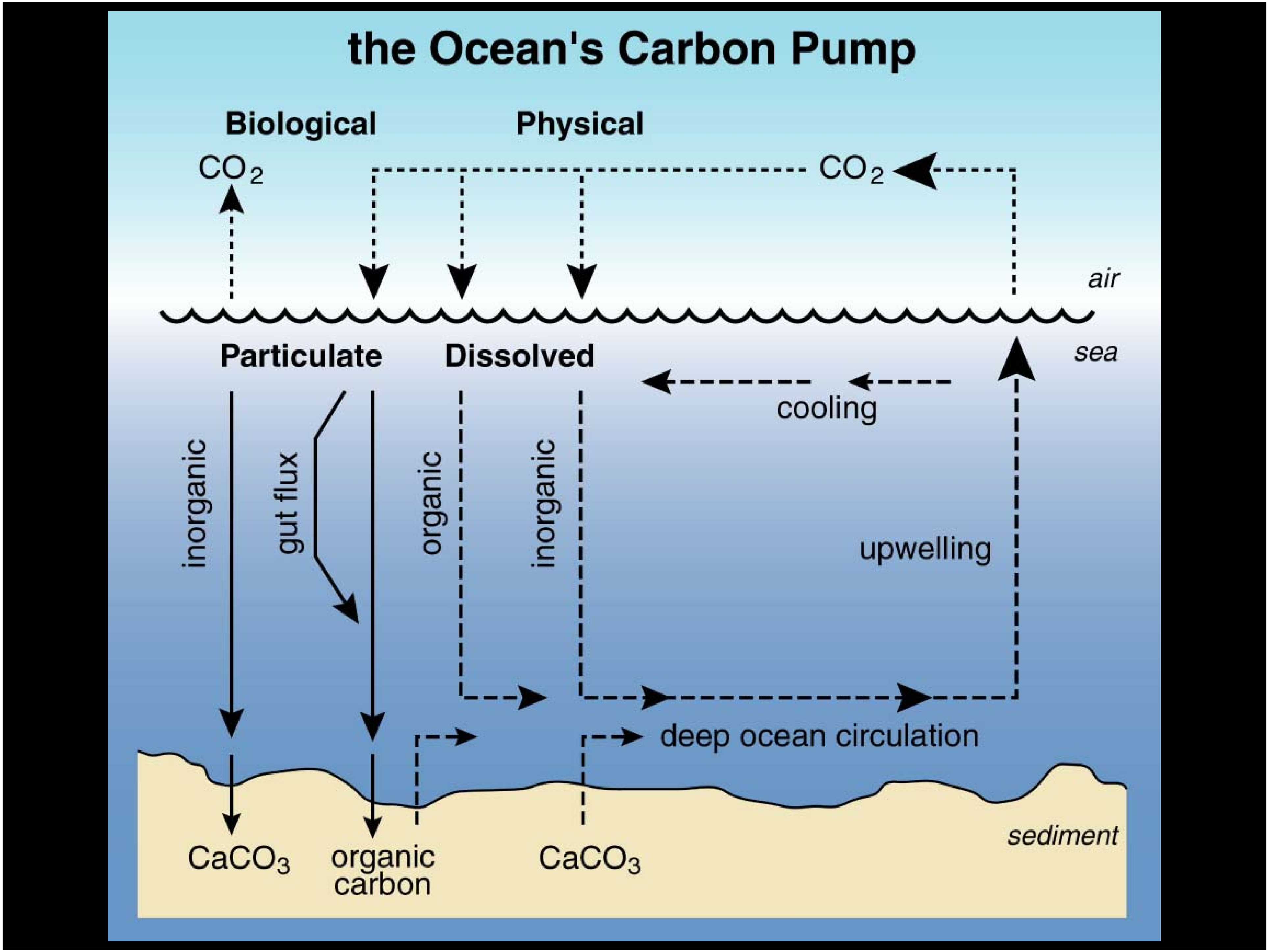
OCEAN'S BIO-C PUMP

- How is it ***structured***?
- How does it ***function***?
- What determines its ***efficiency***?
- How is it linked to ***ocean C sequestration***?

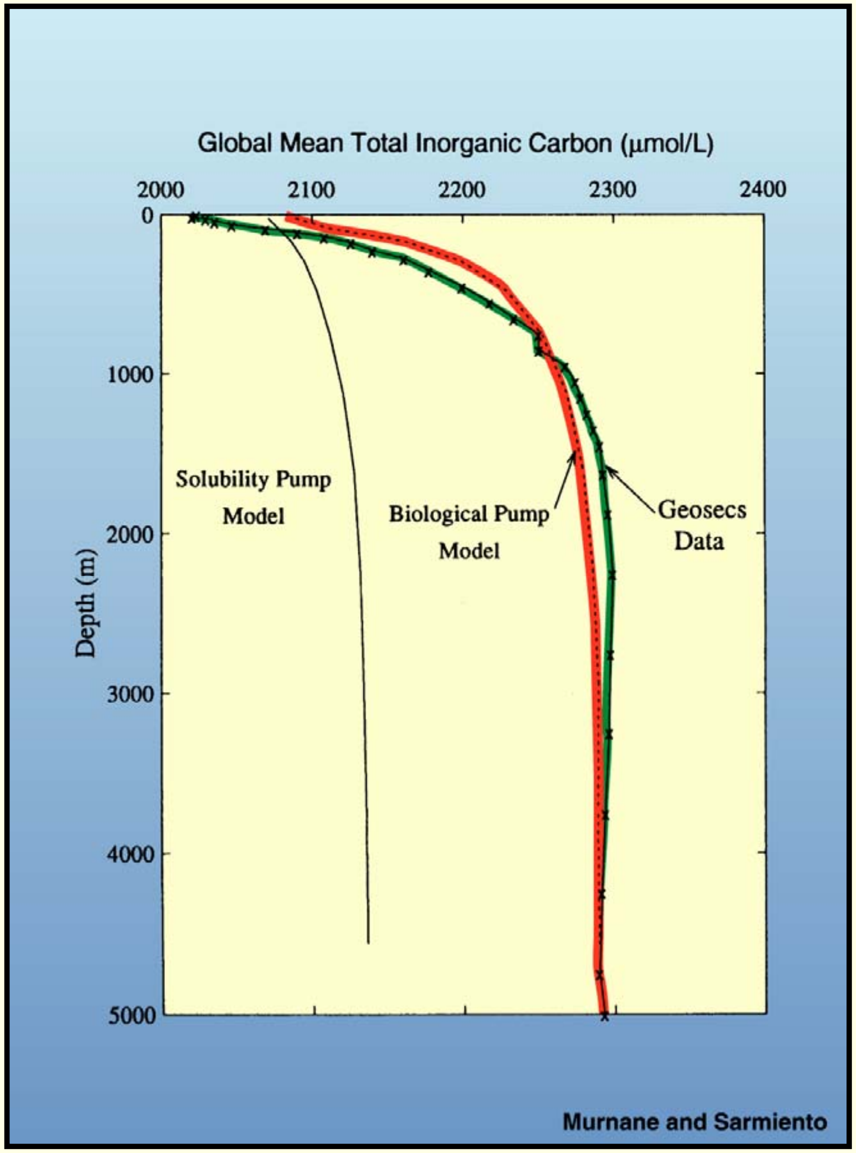






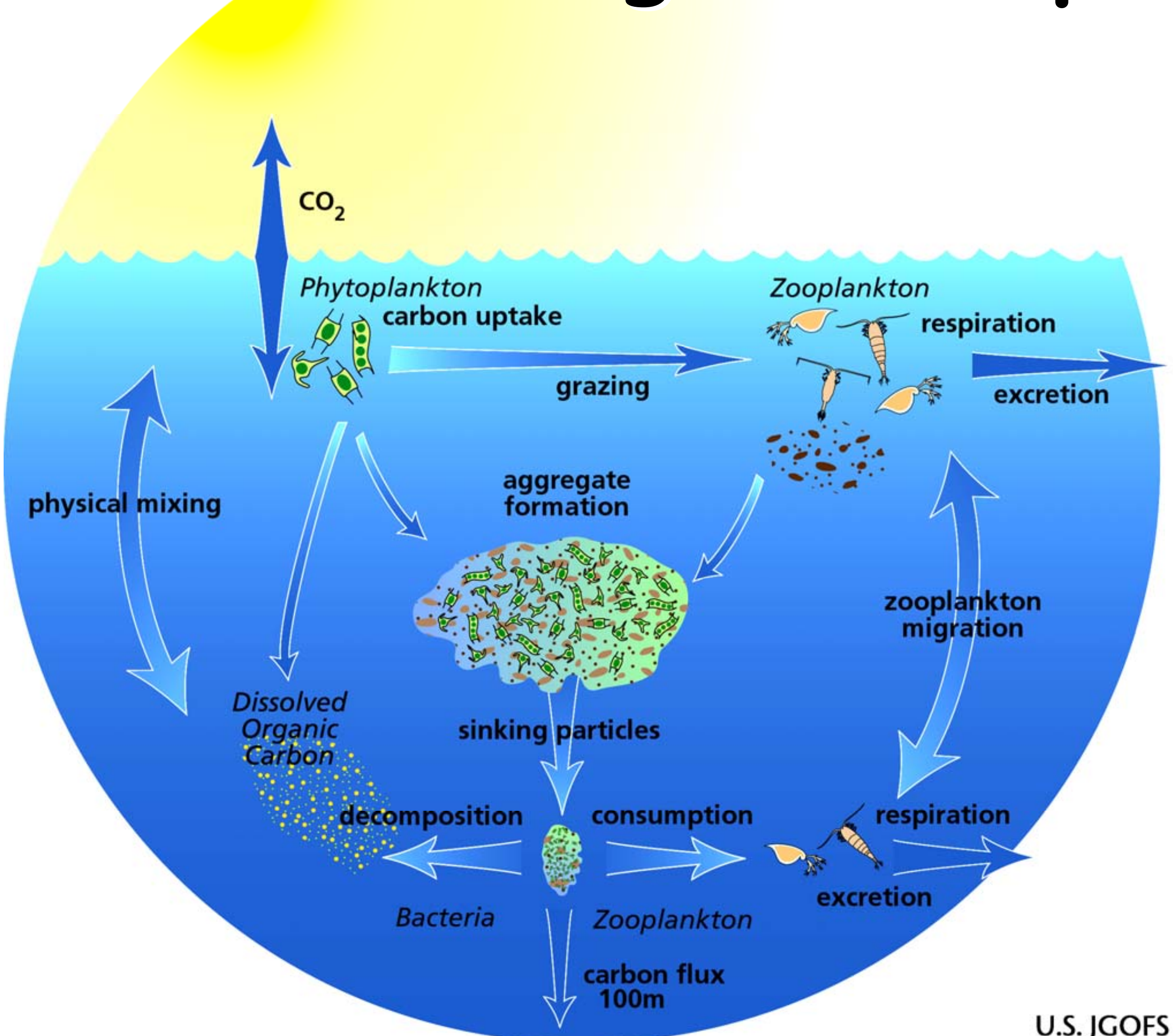


the Ocean's Carbon Pump
Biological
Physical
CO_2
CO_2
air
sea
Particulate
Dissolved
cooling
inorganic
gut flux
organic
inorganic
upwelling
deep ocean circulation
sediment
$CaCO_3$
organic carbon
$CaCO_3$



Model calculations show that Biological Pump is necessary to explain field data

The "Biological Pump"

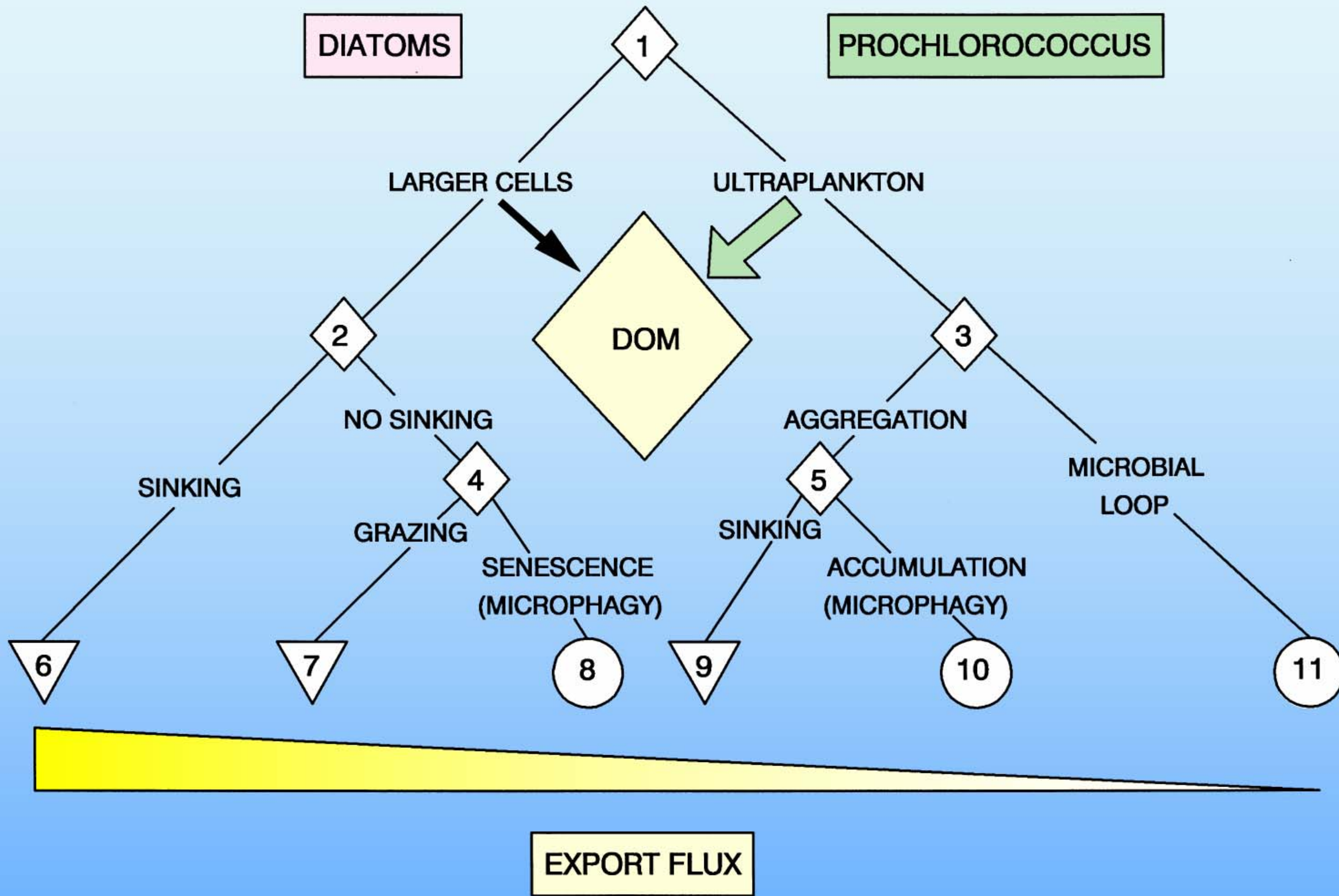


Combined biological processes which transfer organic matter and associated elements to depth

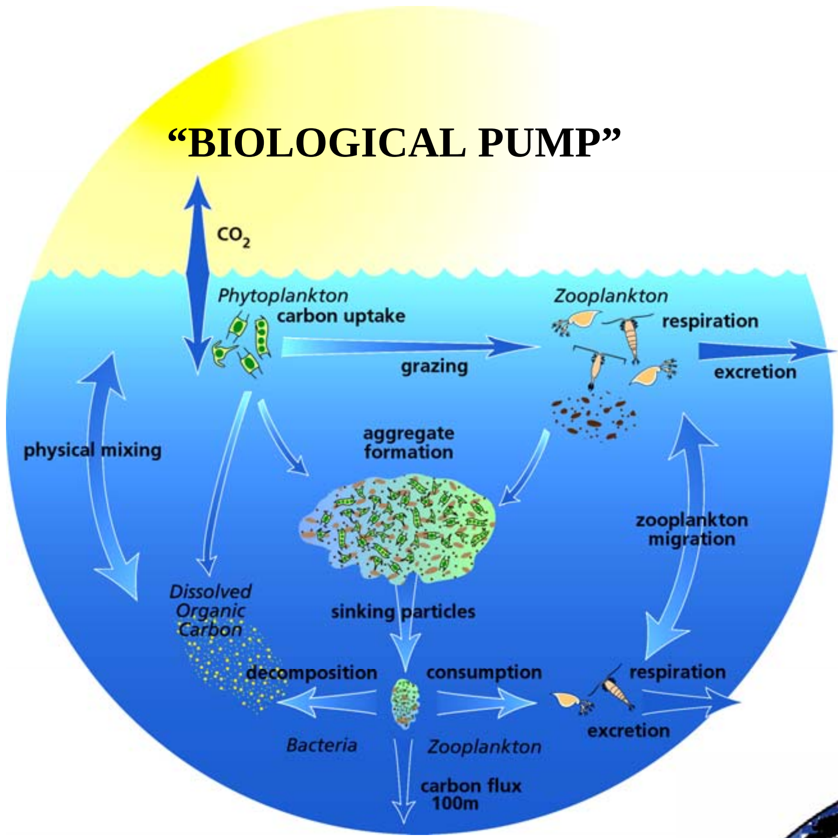
- pathway for rapid C sequestration

Quickly remove C from surface ocean & atm.

- turn off bio pump and 200 ppmv increase atm. CO_2

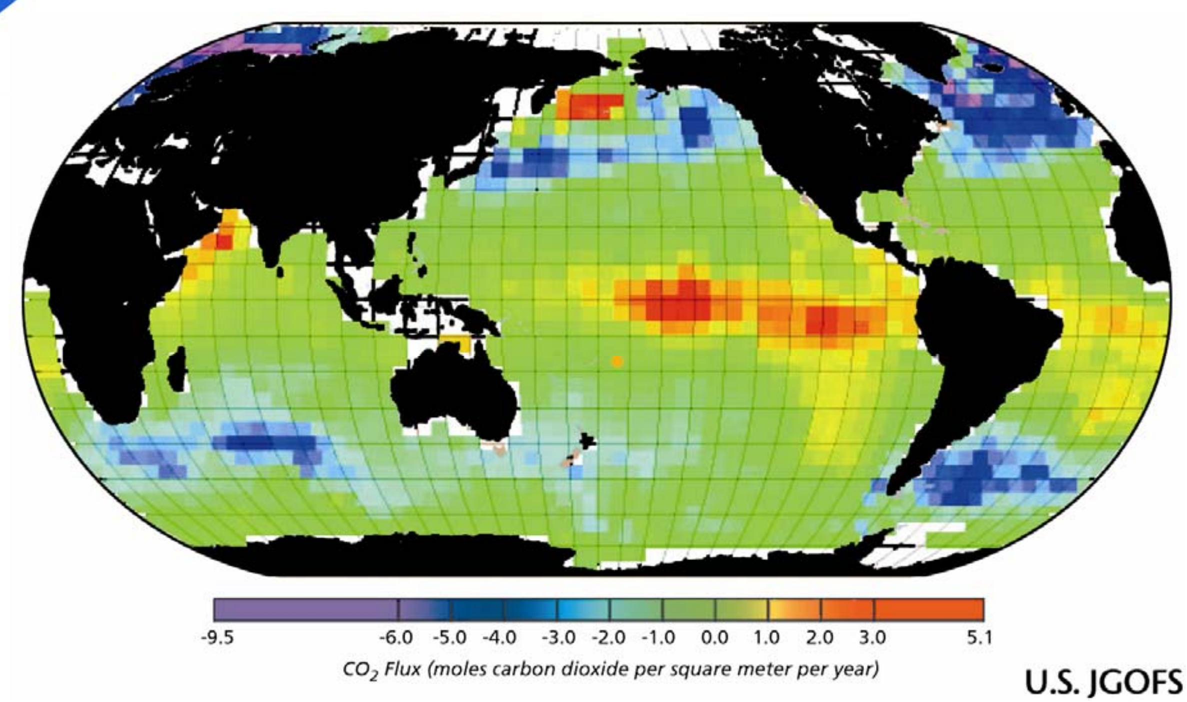


Adapted from Legendre and Le Fèvre (1989)



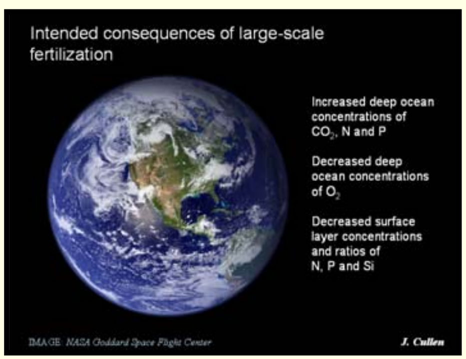
How do we get from the marine food web to a global assessment of CO_2 flux to a mitigation policy???

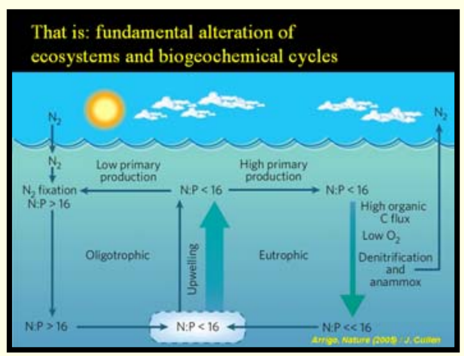
With great difficulty!

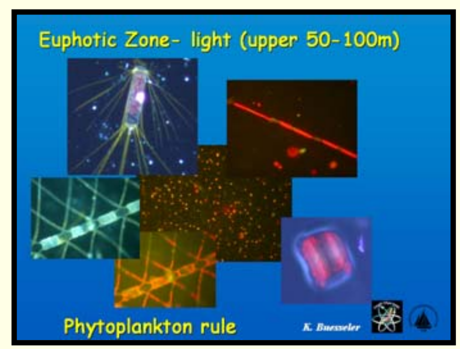


OCEAN NUTRITION OPTIONS FOR (POSSIBLE) C SEQUESTRATION

- ***Fe fertilization of HNLC***
- Fe or Fe/P fertilization of LNLC
- P fertilization in P-stressed regions
- ***Artificial upwelling in open ocean***

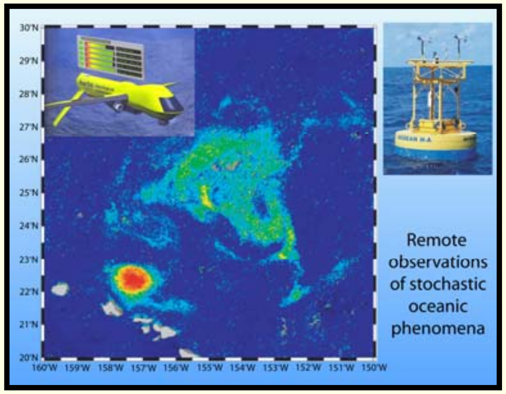






CASE STUDY 1:
Fe fertilization

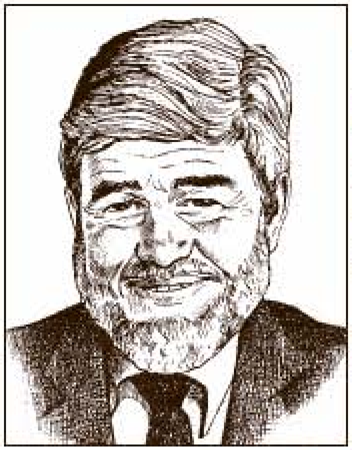
- Site is critical (HNLC)
- Export is key



ON THE SHOULDERS OF GIANTS

John Martin (1935-1993)

by John Weier

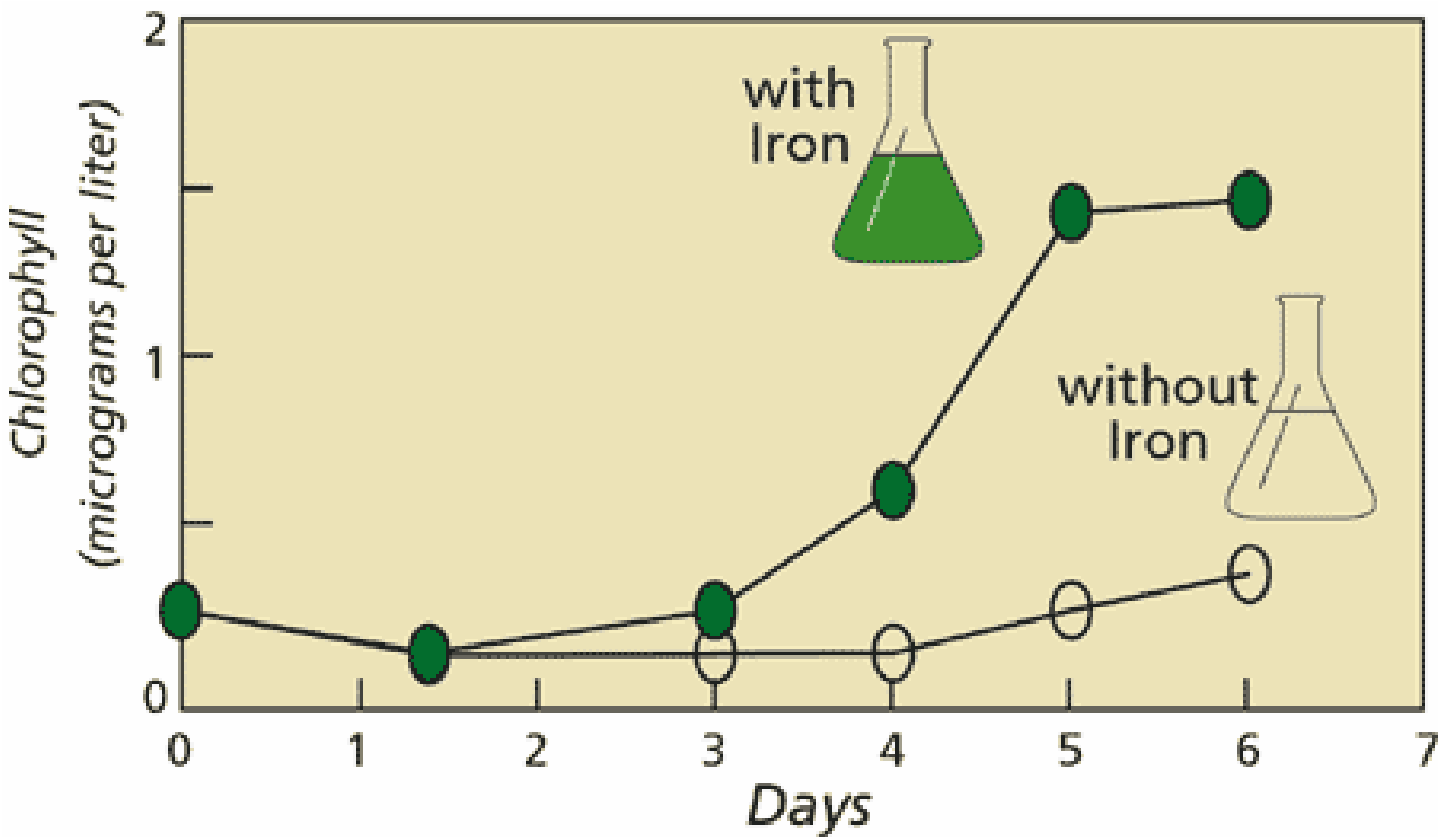


A little over ten years ago at a lecture at the Woods Hole Oceanographic Institution, oceanographer John Martin stood up and said in his best Dr. Strangelove accent, "Give me a half tanker of iron, and I will give you an ice age."

These inflammatory words centered around a theory known as the iron hypothesis. Martin professed that by sprinkling a relatively small amount of iron into certain areas of the ocean, known as high-nutrient, low-chlorophyll zones (HNLCs), one could create large blooms of those unicellular aquatic plants commonly known as algae. If enough of these HNLC zones were fertilized with iron, he believed the growth in algae could take in so much carbon from the atmosphere that they could reverse the greenhouse effect and cool the Earth.

"Give me a half tanker of iron, and I will give you an ice age."

Results from small scale bottle experiments in HNLC region



K. Johnson

Ecosystems (1998) 1: 323±334

ECOSYSTEMS

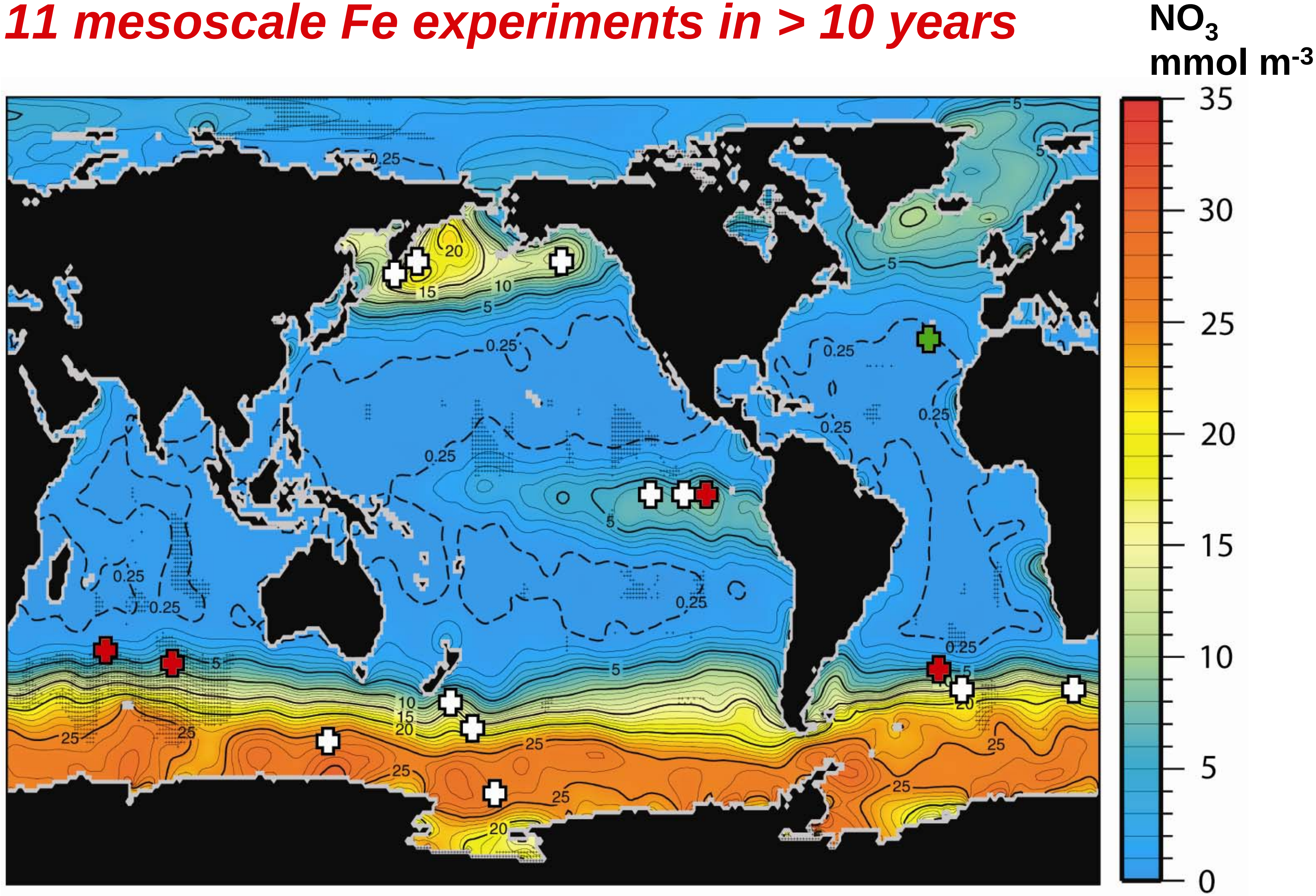
WHOLE-ECOSYSTEM EXPERIMENTS

Replication Versus Realism: The Need for Ecosystem-Scale Experiments

David W. Schindler*

- Compared results of bottle experiments and mesocosms with whole lake observations
- Small scale studies give highly reproducible but spurious results **(no realism!)**
- All problems pale to scale **(time and space)**

11 mesoscale Fe experiments in > 10 years



+Fe (HNLC) High Fe +Fe (LNLC)

Boyd et al. (2007)

TWO KEY REVIEWS

For Dave Karl

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, C09S16, doi:10.1029/2004JC002601, 2005

Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment

Hein J. W. de Baar,[1,2] Philip W. Boyd,[3] Kenneth H. Coale,[4] Michael R. Landry,[5] Atsushi Tsuda,[6] Philipp Assmy,[7] Dorothee C. E. Bakker,[8] Yann Bozec,[1] Richard T. Barber,[9] Mark A. Brzezinski,[10] Ken O. Buesseler,[11] Marie Boyé,[2,12] Peter L. Croot,[1,13] Frank Gervais,[7] Maxim Y. Gorbunov,[14] Paul J. Harrison,[15] William T. Hiscock,[16] Patrick Laan,[1] Christiane Lancelot,[17] Cliff S. Law,[18] Maurice Levasseur,[19] Adrian Marchetti,[20] Frank J. Millero,[16] Jun Nishioka,[21] Yukihiro Nojiri,[22] Tim van Oijen,[2] Ulf Riebesell,[13] Micha J. A. Rijkenberg,[1,2] Hiroaki Saito,[23] Shigenobu Takeda,[24] Klaas R. Timmermans,[1] Marcel J. W. Veldhuis,[1] Anya M. Waite,[25] and Chi-Shing Wong[26]

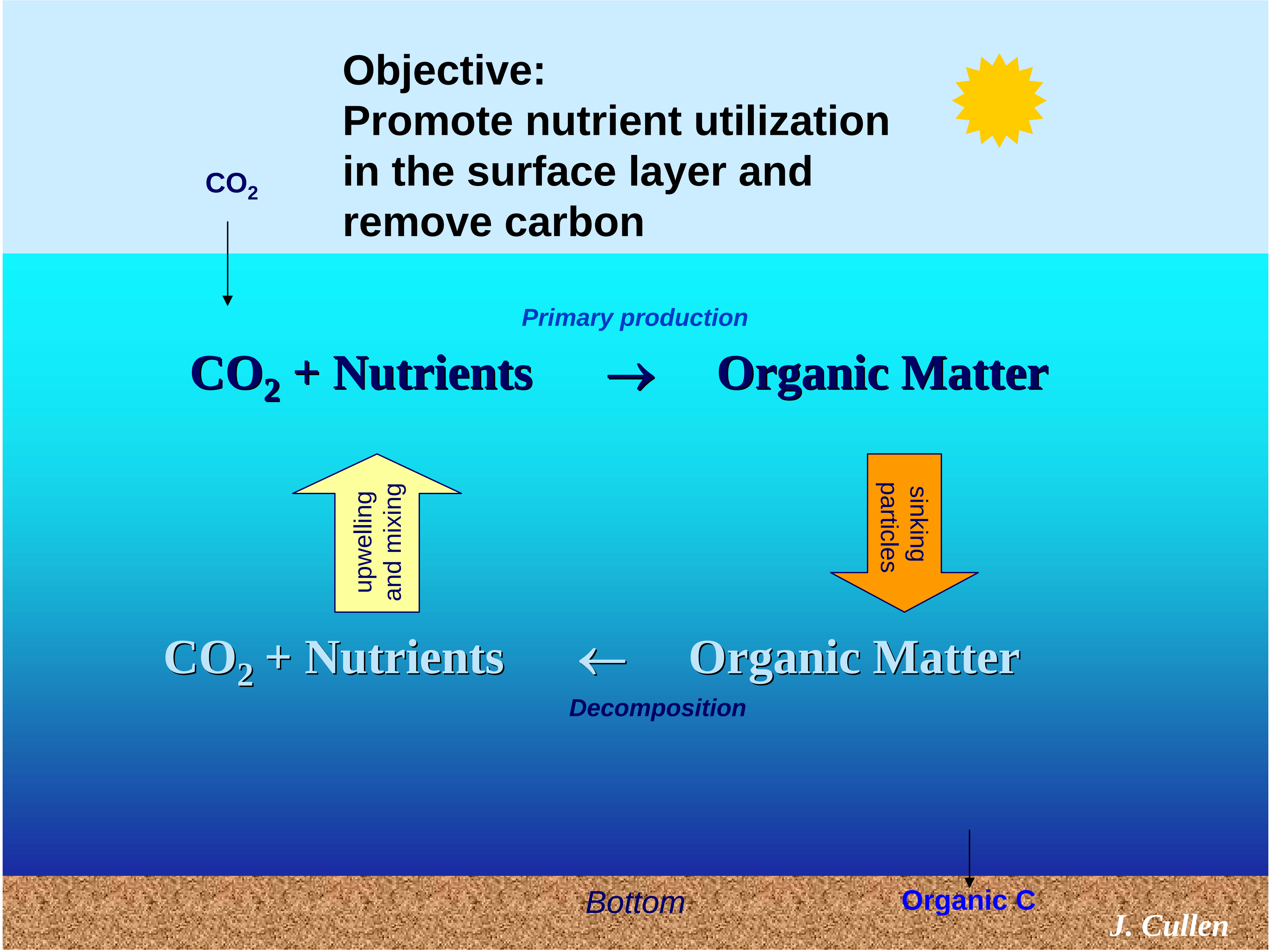
Received 16 July 2004; revised 8 May 2005; accepted 14 July 2005; published 28 September 2005.

de Baar et al.
(2005)
JGR 110

Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions

P. W. Boyd,[1]* T. Jickells,[2] C. S. Law,[3] S. Blain,[4] E. A. Boyle,[5] K. O. Buesseler,[6] K. H. Coale,[7] J. J. Cullen,[8] H. J. W. de Baar,[9] M. Follows,[5] M. Harvey,[3] C. Lancelot,[10] M. Levasseur,[11] N. P. J. Owens,[12] R. Pollard,[13] R. B. Rivkin,[14] J. Sarmiento,[15] V. Schoemann,[10] V. Smetacek,[16] S. Takeda,[17] A. Tsuda,[18] S. Turner,[2] A. J. Watson[2]

Boyd et al.
(2007)
Science 315


Objective:
Promote nutrient utilization in the surface layer and remove carbon
CO_2
Primary production
CO_2 + Nutrients → Organic Matter
upwelling and mixing
sinking particles
CO_2 + Nutrients ← Organic Matter
Decomposition
Bottom
Organic C
J. Cullen

Intended consequences of large-scale fertilization

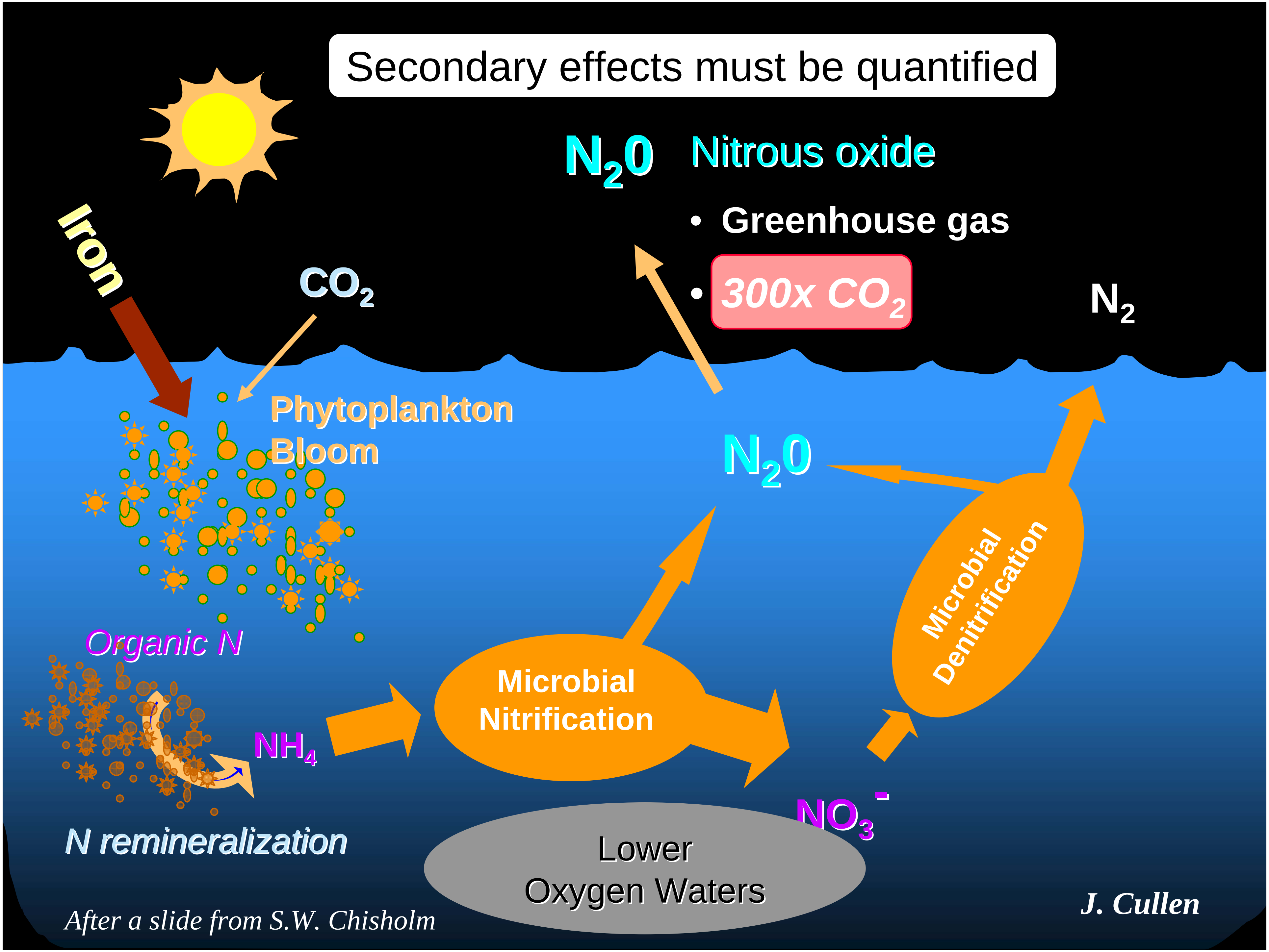
Increased deep ocean concentrations of CO_2, N and P

Decreased deep ocean concentrations of O_2

Decreased surface layer concentrations and ratios of N, P and Si

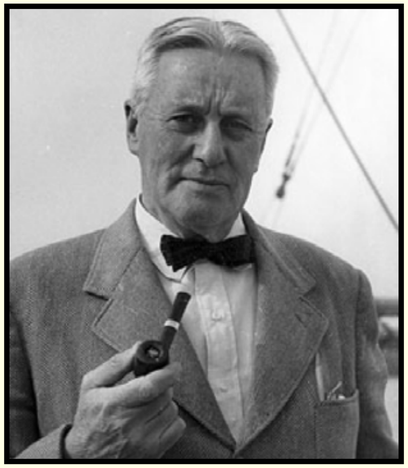
IMAGE: *NASA Goddard Space Flight Center*

J. Cullen


Secondary effects must be quantified
Iron
CO_2
N_20
Nitrous oxide
• Greenhouse gas
• 300x CO_2
N_2
Phytoplankton
Bloom
N_20
Microbial
Denitrification
Organic N
NH_4
Microbial
Nitrification
NO_3^-
N remineralization
Lower
Oxygen Waters
J. Cullen
After a slide from S.W. Chisholm

A.C. REDFIELD (1958)

“The inadequacy of experiments in marine biology”

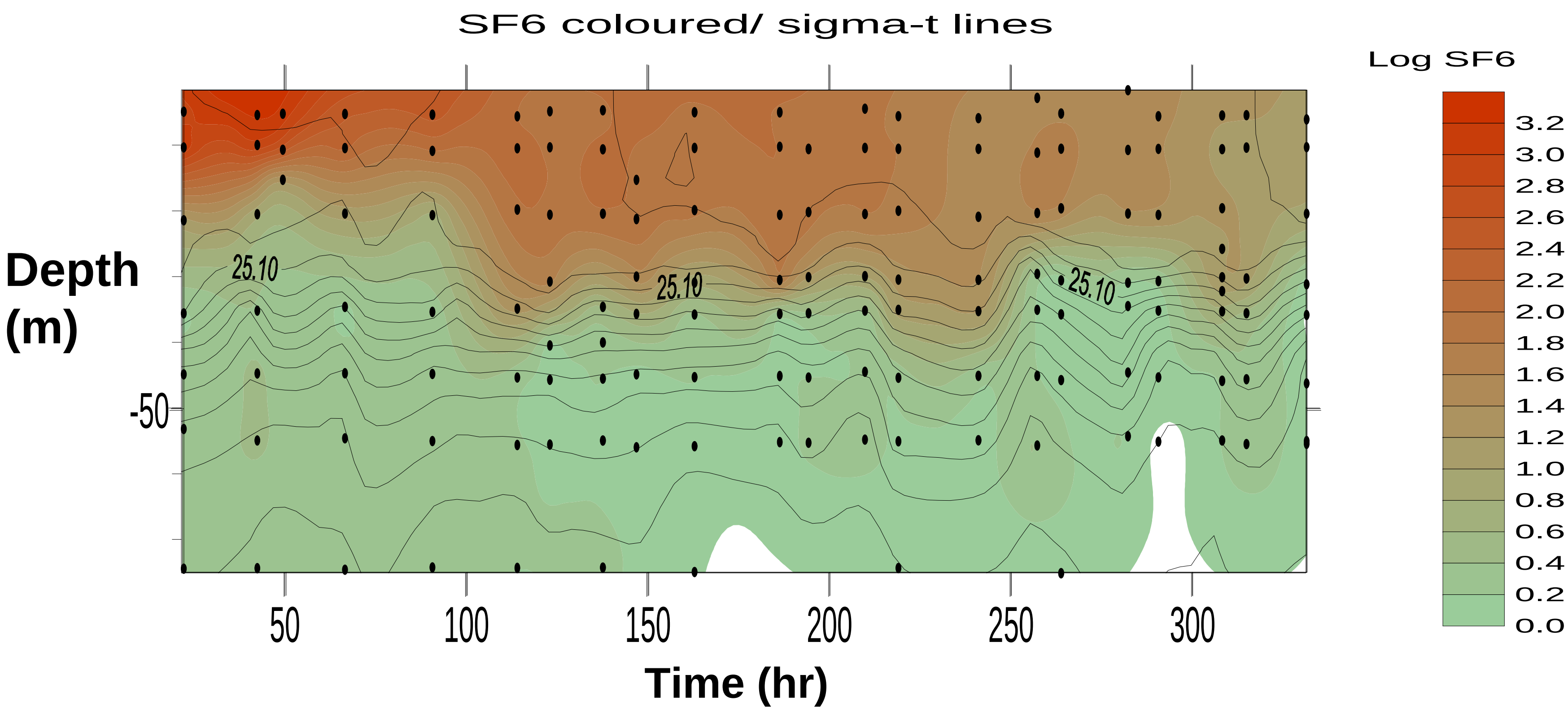


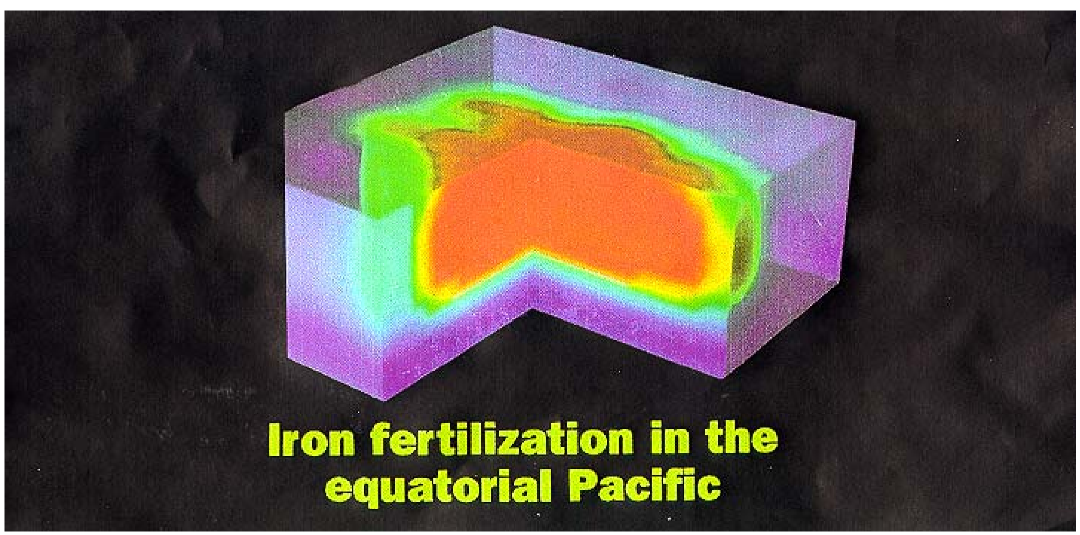
C:N:P

- Ecosystem manipulation/perturbation experiments are essential
- Complex systems must be thoroughly described and well understood *before* relevant experiments can be conducted

Iron is added with SF_6 as inert tracer for dilution

P. Boyd



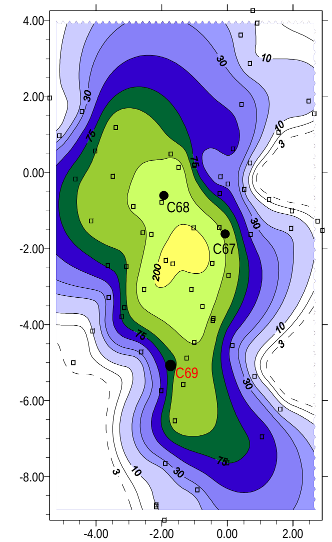


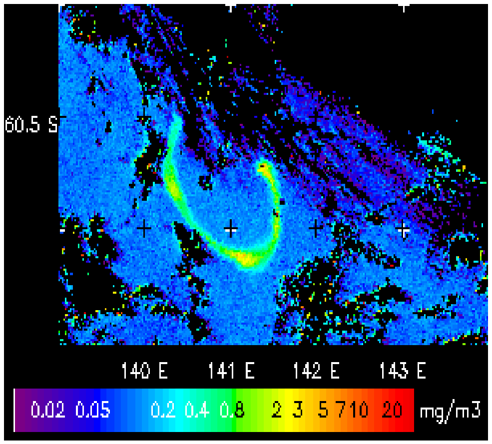
Behrenfeld et al. (1996)

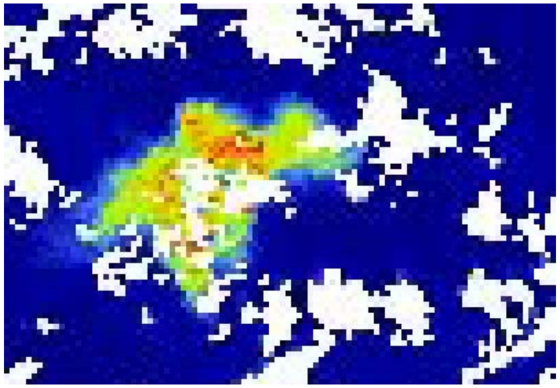
P. Boyd

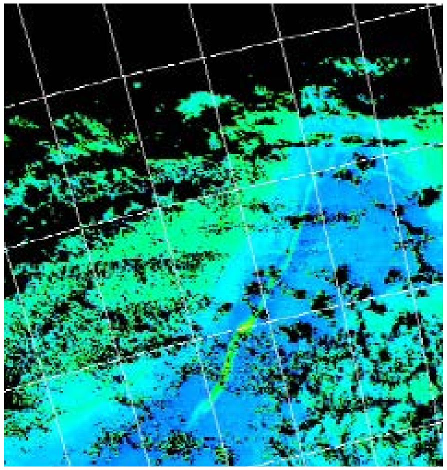
Common findings in mesoscale iron experiments

A similar experimental design was used in all studies





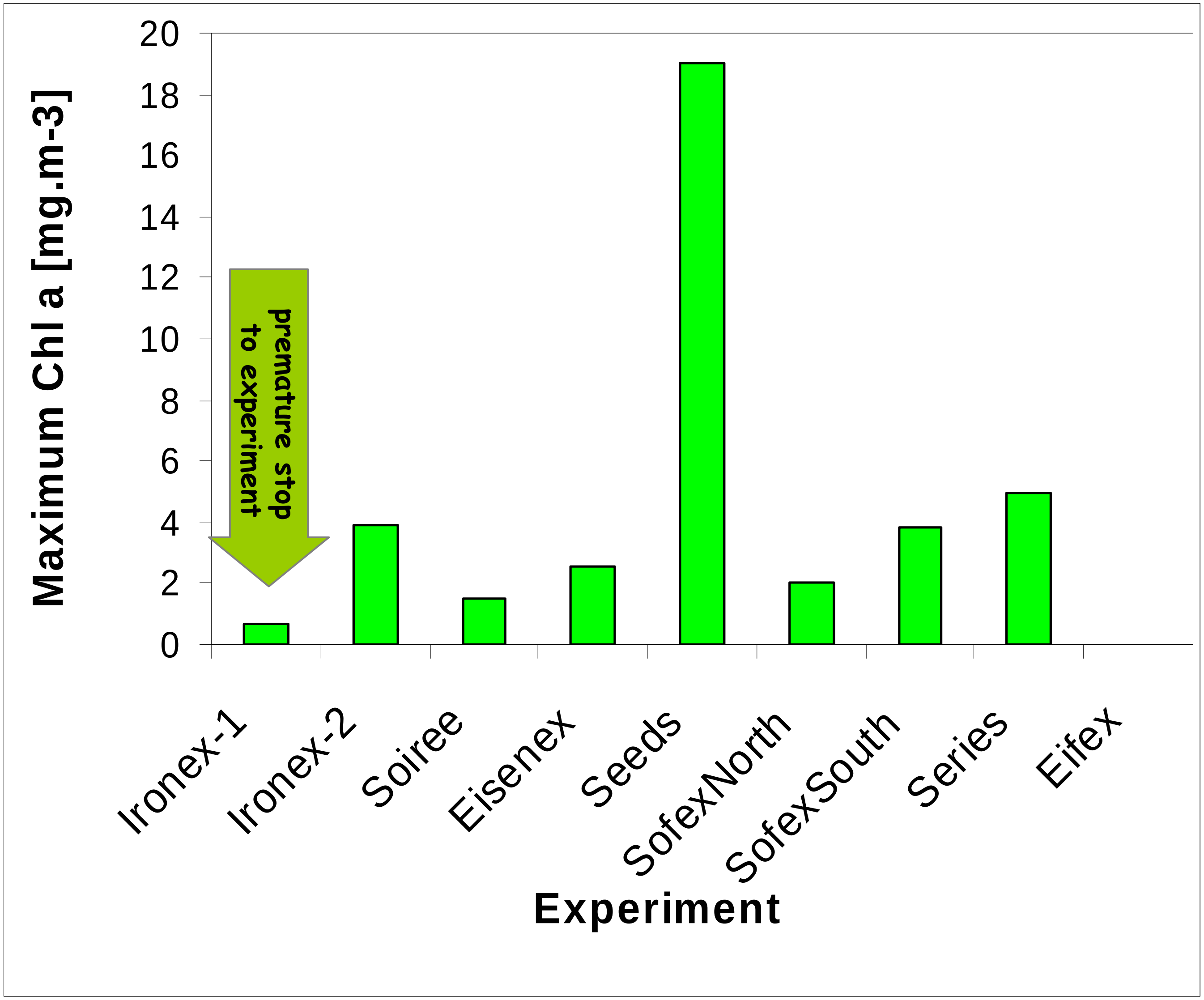




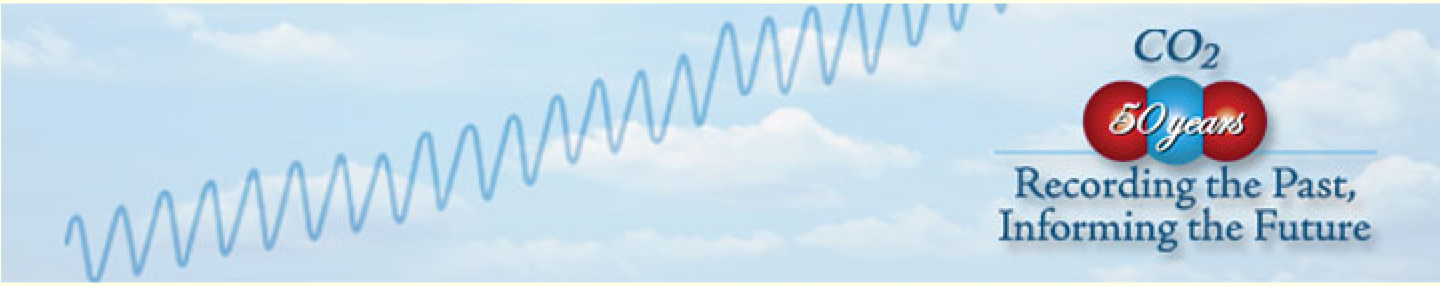
Virtually all experiments resulted in blooms

P. Boyd

A wide range in bloom signatures



De Baar et al. (2005) / P. Boyd



"Iron fertilization is not a silver bullet … let's look at it on our portfolio for mitigation … uncertainty shouldn't preclude research"

Margaret Leinen, Climos

"There is a limited amount of money and time … the worst possible thing would be to invest in something that doesn't work and has big impacts that we don't anticipate"

Lisa Speer, Natural Resources Defense Council

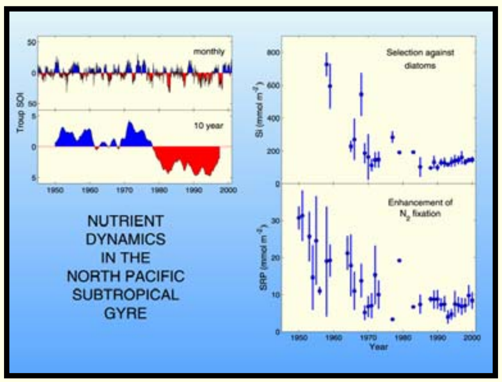
H. Powell, *Oceanus* article, Nov 2007

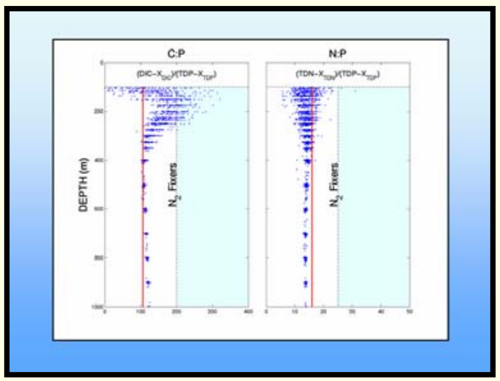
SUMMARY:
HNLC Fe Fertilization

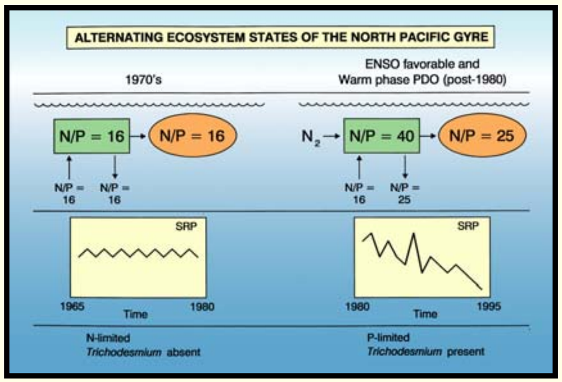
- Add Fe → Bloom
- Unresolved issues
  - C:Fe stoichiometry
  - C export ??
  - Unexpected ecosystem consequences (CH_4, N_2O production)
  - Patch-to-system scaling considerations

CASE STUDY 2:
Artificial Upwelling

- Site is critical (C-N-P)
- Community succession is key
- C-N-P Stoichiometry is key





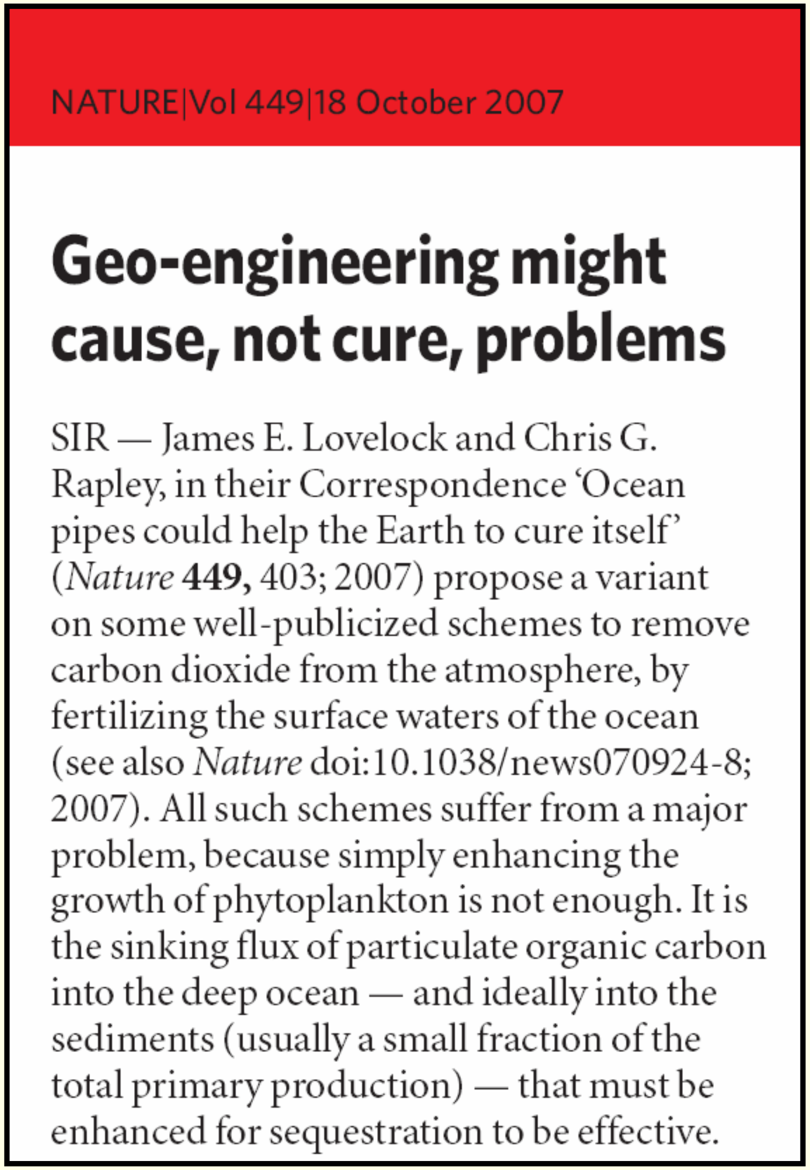


NATURE|Vol 449|27 September 2007

Ocean pipes could help the Earth to cure itself

SIR — We propose a way to stimulate the Earth's capacity to cure itself, as an emergency treatment for the pathology of global warming.

J. E. Lovelock and C. G. Rapley (2007)


NATURE|Vol 449|18 October 2007

Geo-engineering might cause, not cure, problems

SIR — James E. Lovelock and Chris G. Rapley, in their Correspondence 'Ocean pipes could help the Earth to cure itself' (*Nature* **449,** 403; 2007) propose a variant on some well-publicized schemes to remove carbon dioxide from the atmosphere, by fertilizing the surface waters of the ocean (see also *Nature* doi:10.1038/news070924-8; 2007). All such schemes suffer from a major problem, because simply enhancing the growth of phytoplankton is not enough. It is the sinking flux of particulate organic carbon into the deep ocean — and ideally into the sediments (usually a small fraction of the total primary production) — that must be enhanced for sequestration to be effective.

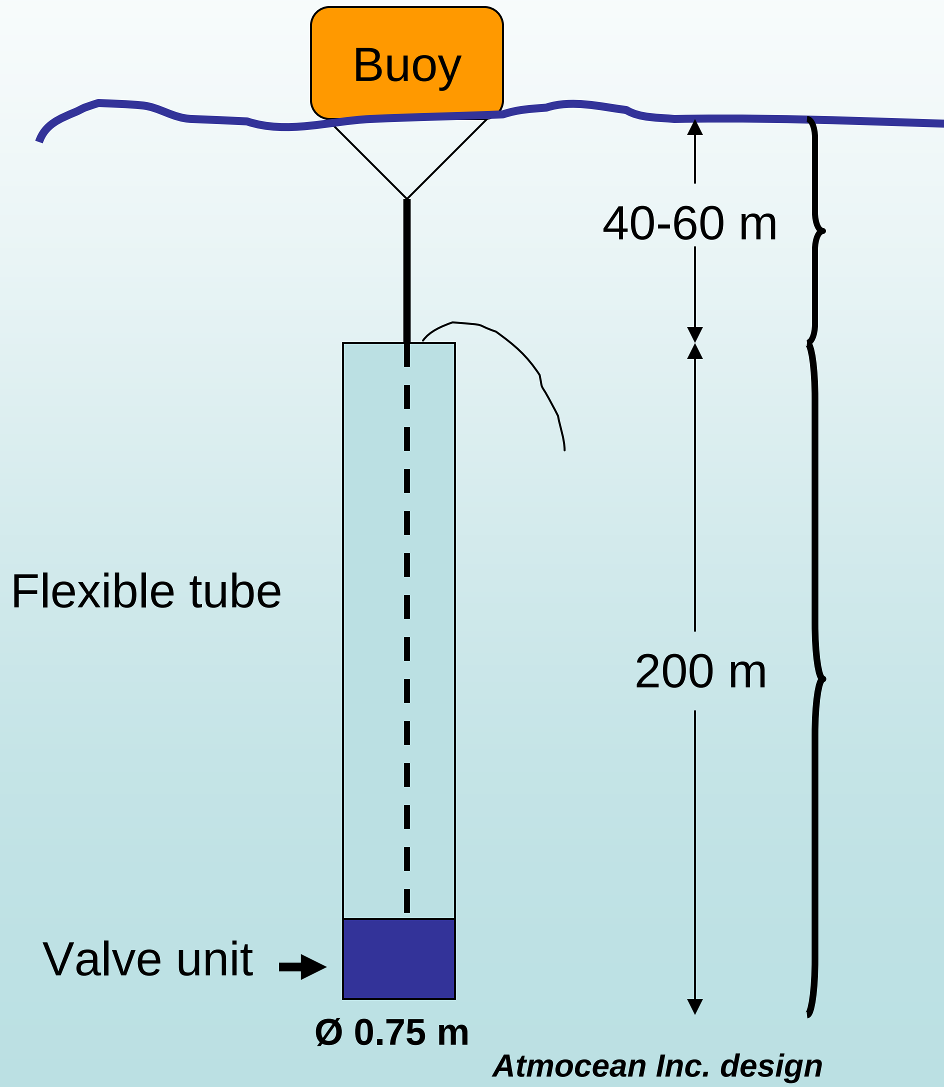
Immediate retort from the science community… essentially "What are you smoking in those pipes?"

The issue has to do with the CNP ratio of upwelled water relative to particle export

Nothing's as fundamental as elemental!!

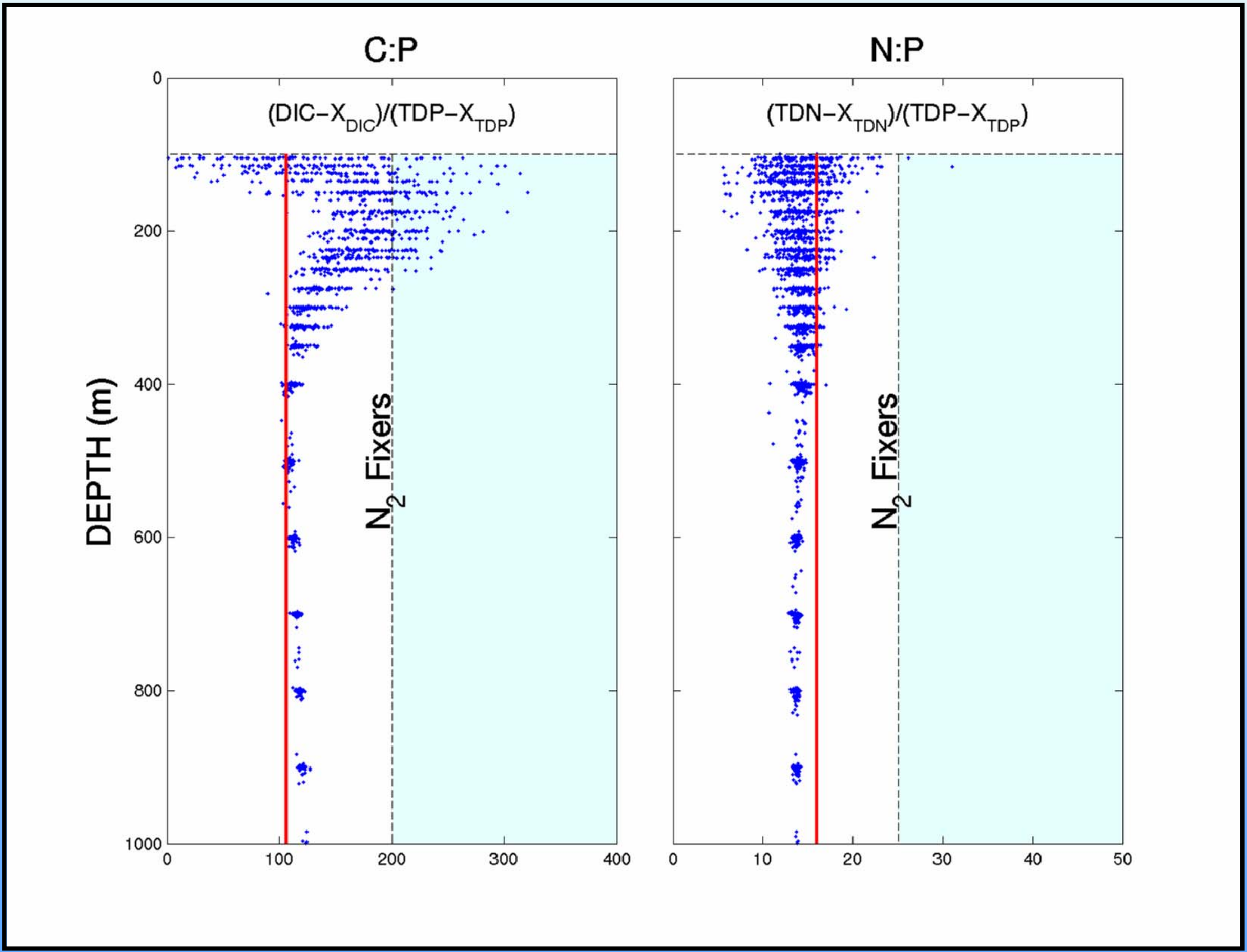
J. Shepherd et al. 2007

Bloom creation –
wave driven ocean upwelling pumps

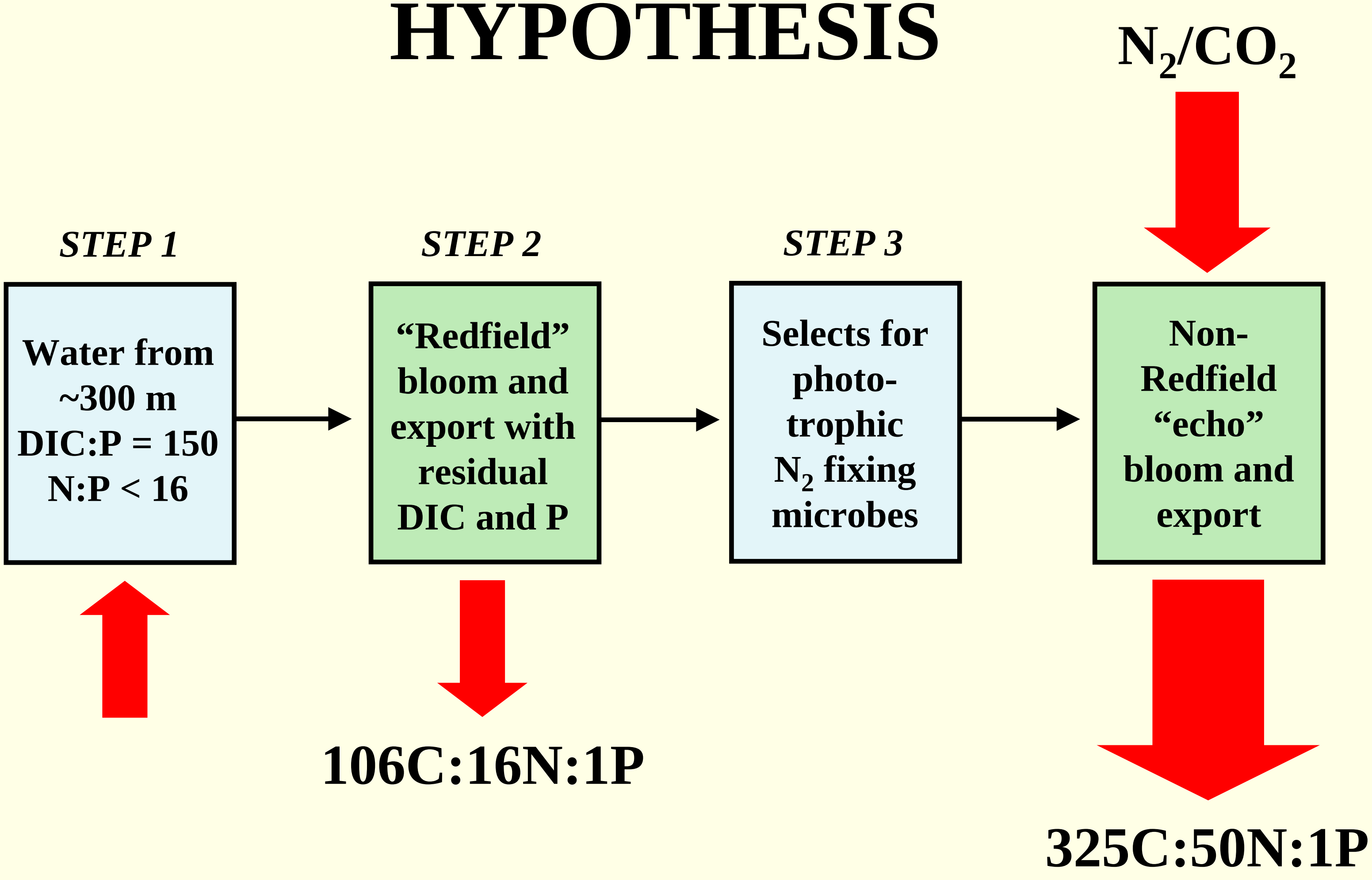


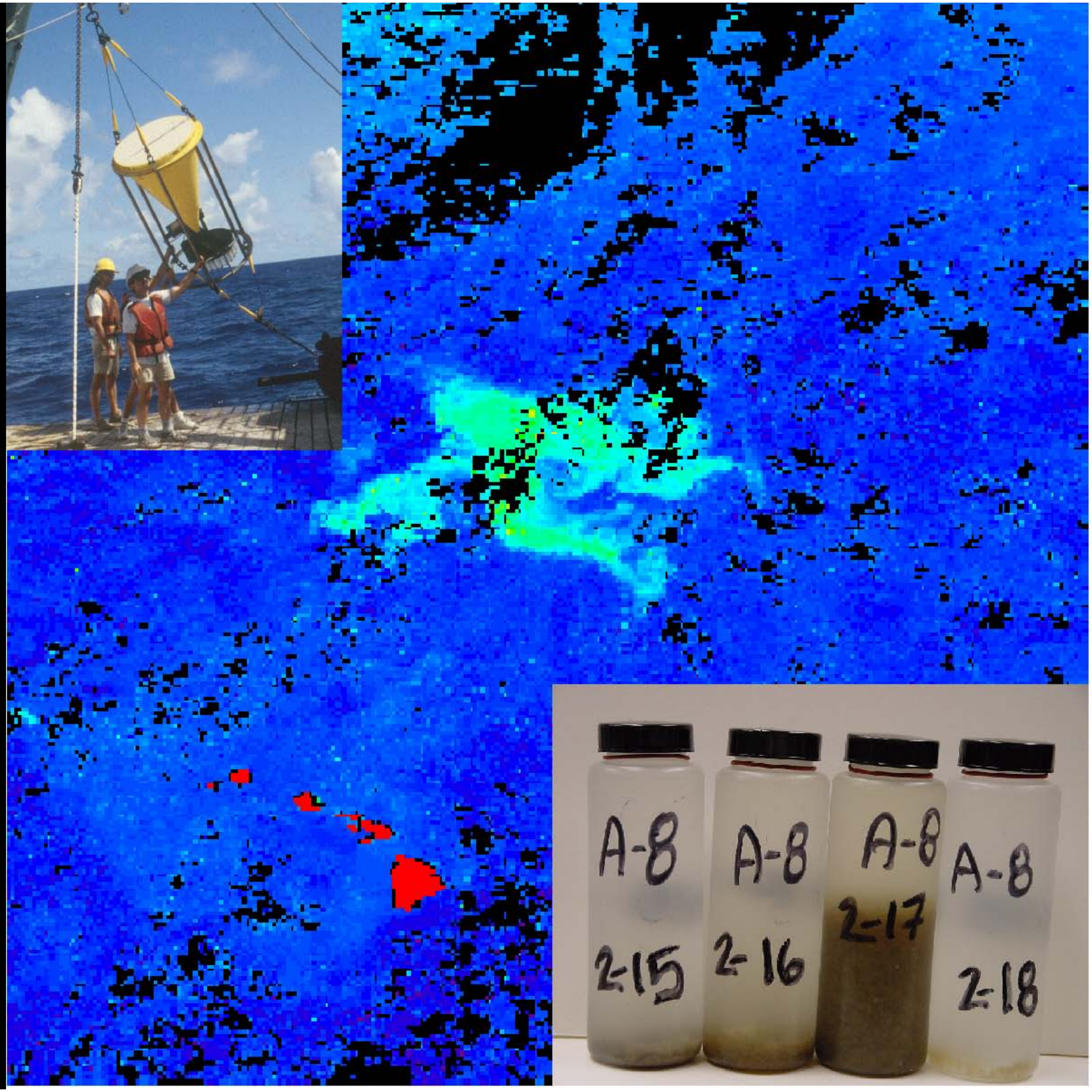
- Transfer nutrients by "sea elevator"
- Remove C by bio-pump
- Net result depends on ocean chemistry, microbial community structure and luck

STA. ALOHA (1988-2007)



STA. ALOHA UPWELLING HYPOTHESIS




A-8
2-15
A-8
2-16
A-8
2-17
A-8
2-18

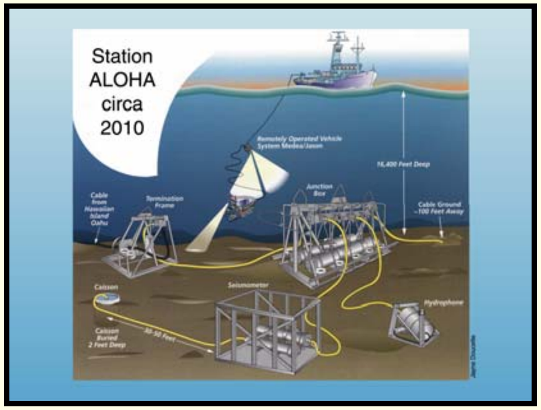
SUMMARY:
ARTIFICIAL UPWELLING

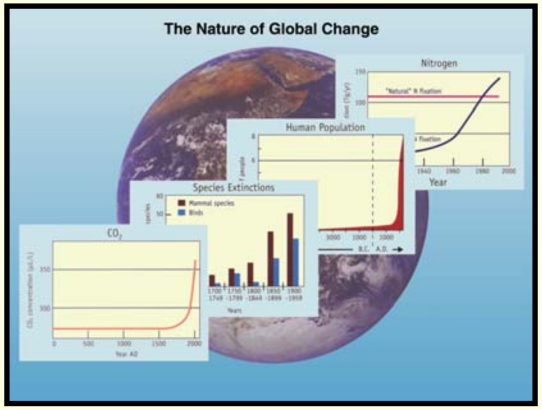
- Deep-water nutrient loading of LNLC regions $\rightarrow$ Bloom
- Plankton community succession leads to N_2 fixation if upwelled N:P is lower than Redfield Ratio
- C sequestration trajectory and efficiency may be more predictable than in Fe fertilization experiments

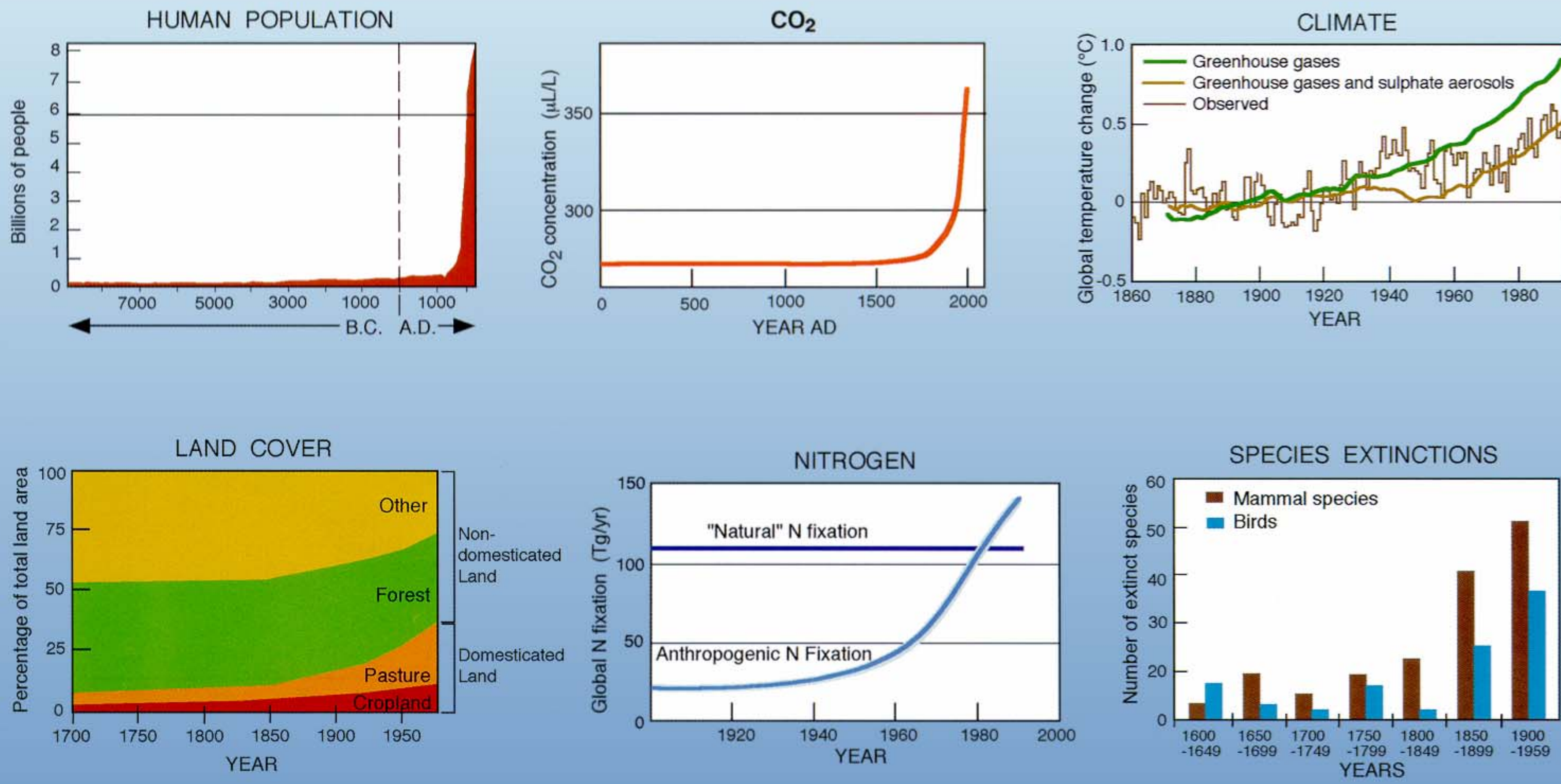
“We are just at the threshold of our knowledge of the oceans… this knowledge is more than a curiosity, our very survival may hinge on it.”

John F. Kennedy

FUTURE RESEARCH PROSPECTUS

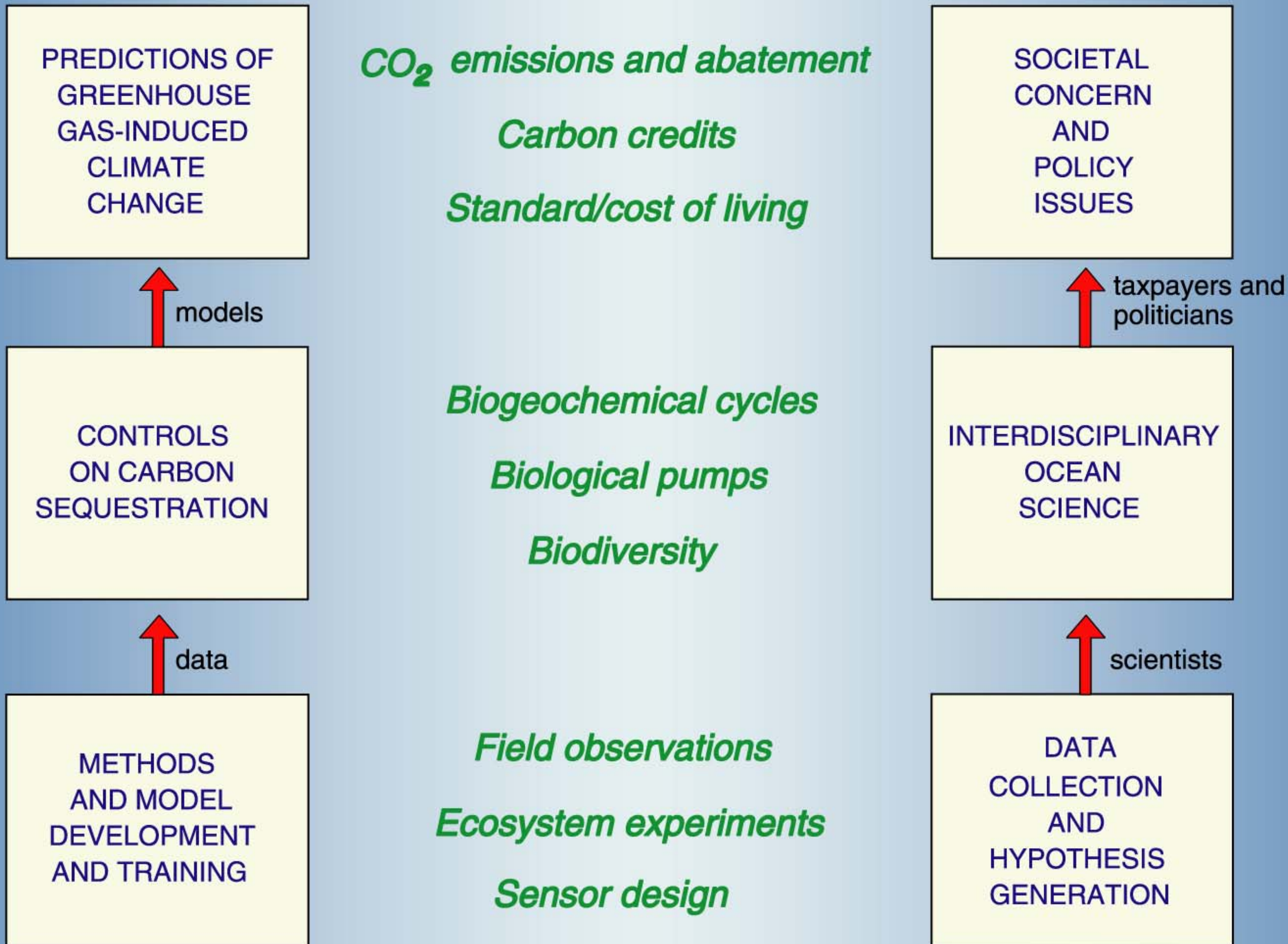






IGBP-Global Change

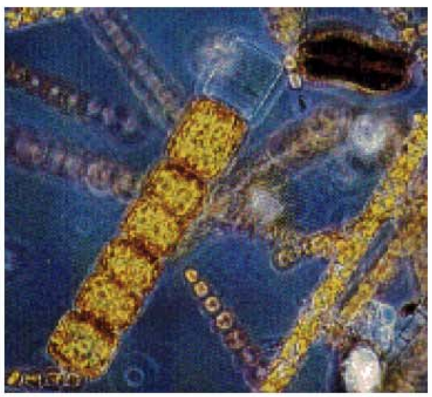
Science – Society Connections



Is ocean fertilization a viable "stabilization wedge" option?

- Scientific jury is still out
- Ecology always trumps economics and policy
- Environmental impacts not well constrained
- Import of export

"Moving ahead with uncertainty"



An Ethics Code for Ocean Carbon Experiments

By Eli Kintisch
*Science*NOW Daily News
10 October 2007

Scientists and entrepreneurs alike are abuzz over iron fertilization, a controversial technique that uses iron-seeded plankton to sequester atmospheric carbon for centuries deep underwater. Now, a San Francisco-based climate startup called Climos has proposed a code of conduct to address contentious aspects of how experiments are conducted.

BEST PRACTICES & CODE OF CONDUCT

- Permits (notwithstanding ambiguity of need)
- Environmental assessments
- Avoid marine protected areas
- Transparency, peer review / published, collaboration

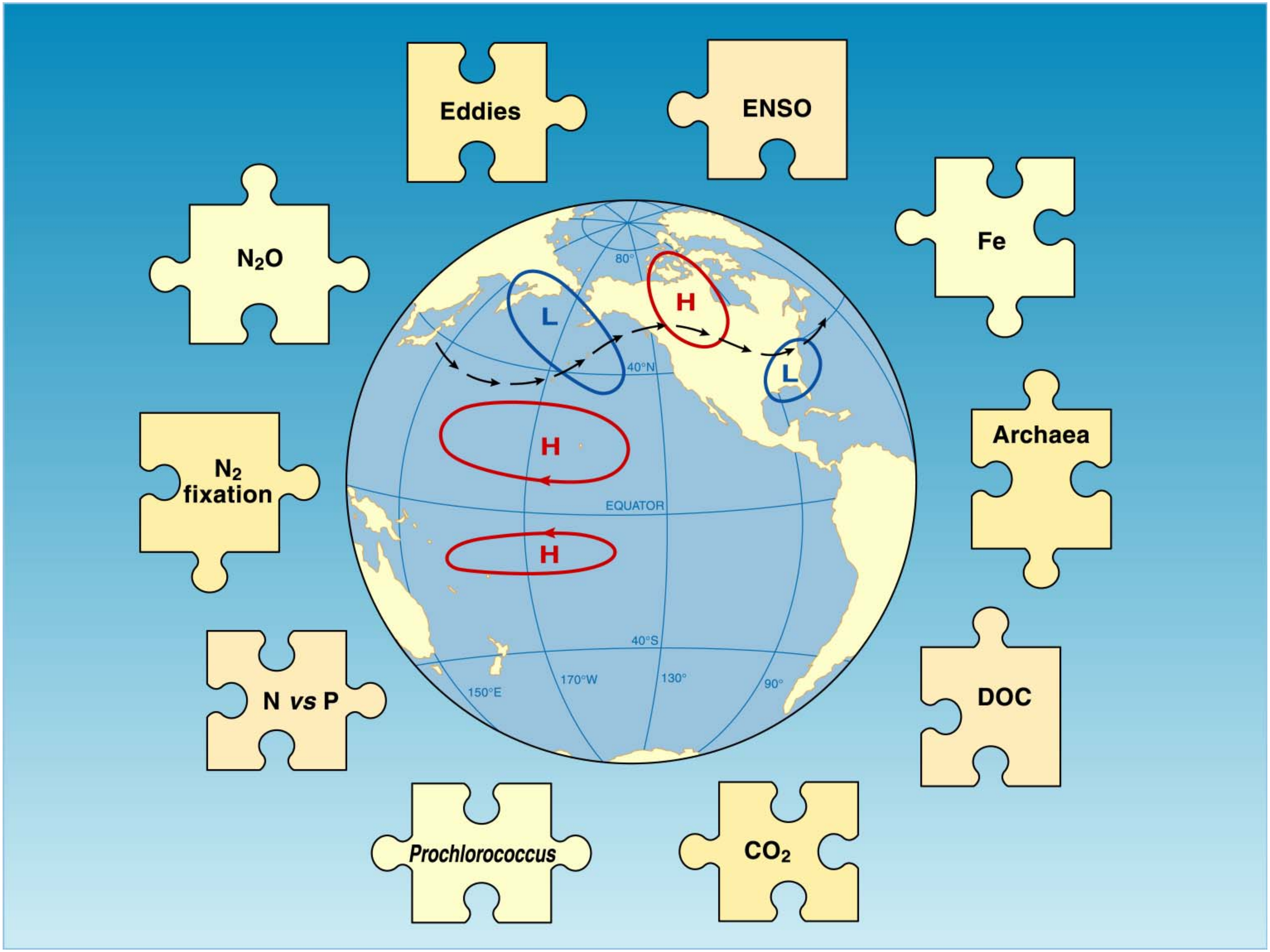
http://www.climos.com

Manoa Climate Change Commission

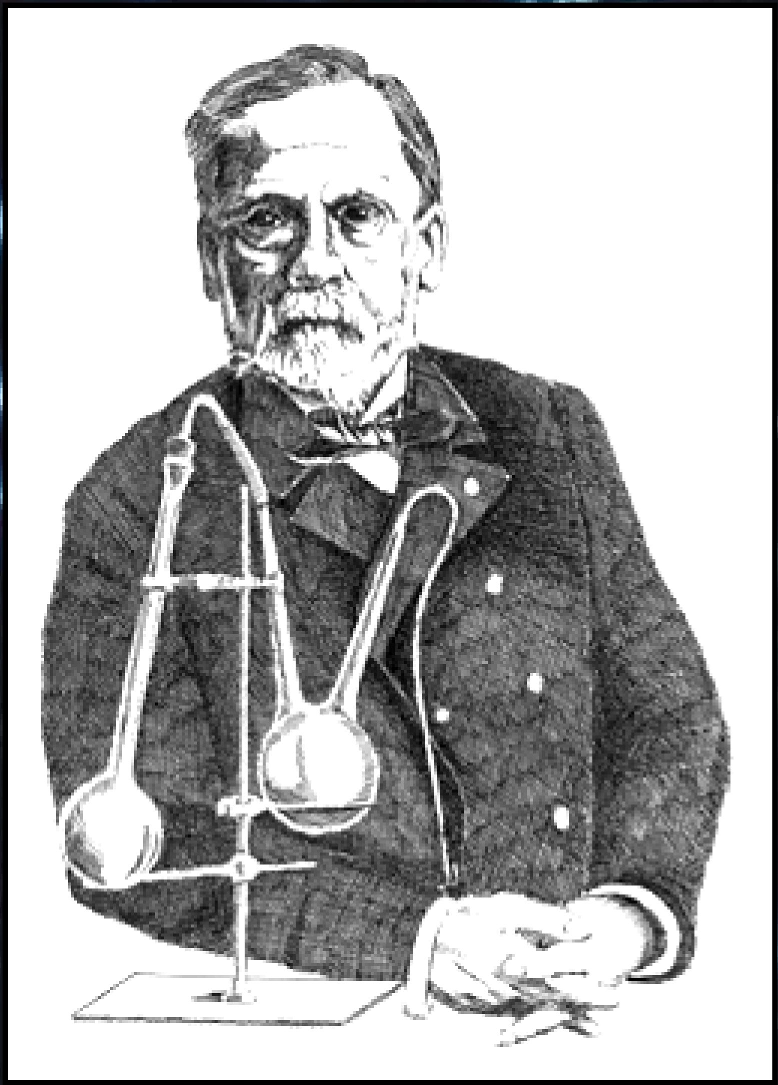
- Established Feb 2007
- Lorenz Magaard, Chair

Task Force Global Climate Change Solutions Act of 2007

- Maurice Kaya / Laurence Lau, co-Chairs
- Lorenz Magaard and Makena Coffman, members



Eddies
ENSO
N_2O
Fe
L
H
80°
40°N
L
H
Archaea
N_2 fixation
EQUATOR
H
40°S
150°E
170°W
130°
90°
N *vs* P
DOC
Prochlorococcus
CO_2



“It is the microbes that will have the last word”

Louis Pasteur