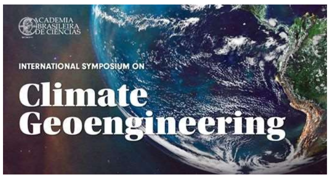


Academia Brasileira de Ciências
Rio de Janeiro 10/06 - 11/06

Give me half a tanker of iron and I'll give you the next ice age (John Martin) - Reflexões sobre a resposta dos ecossistemas marinhos à projetos de geoengenharia

Frederico Brandini
Instituto Oceanográfico
Universidade de São Paulo
brandini@usp.br

1

Summary

- The structure and functioning o marine ecosystems
- Why iron is important for biological systems?
- Phytoplankton primary production and nutrient uptake ratio
- The oceanic "biological pump"
- The high nutrient-low chlorophyll areas of the global ocean
- The "iron hypothesis" and the early experiments of ocean fertilization
- Results of the large-scale iron fertilization experiments
- Modelling the impacts of iron enrichment on the marine biodiversity
- Effectiveness of ocean mass fertilization with iron

2

Global Carbom organic carbom production

through plant photosynthesis = 104 GtC/ano*

Terrestrial:	56 GtC/ano (54%)
Oceanic:	48 GtC/ano (46%)*

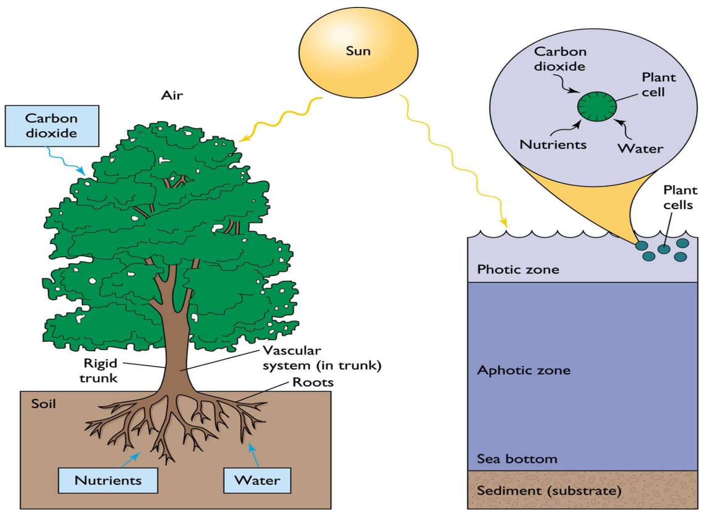
Oceanic plant biomass is 1000x smaller than the terrestrial biomass. Why and how is it stored in the ocean?

* 1Gt =10^{15}g
* > **90% from phytoplankton**

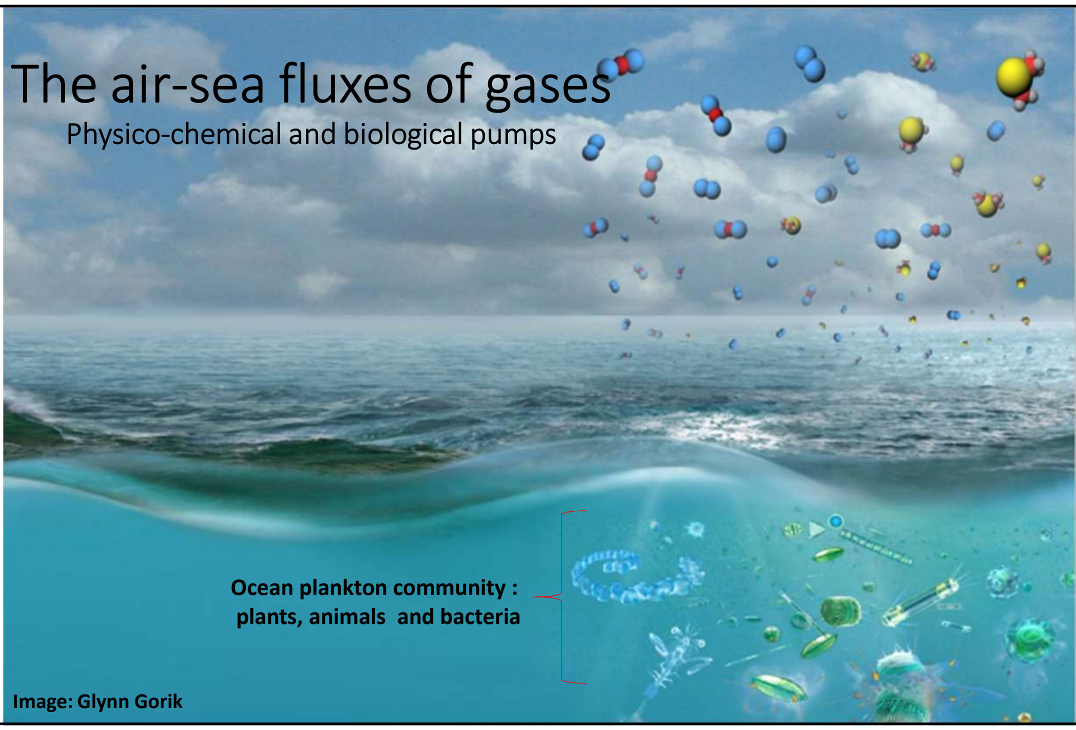
3

Terrestrial and oceanic organic Carbon stocks

(same ecological processes *vs* different ecological machinary)



4



5

Marine phytoplankton ?

> Microalgae cells are main primary producers in the oceans

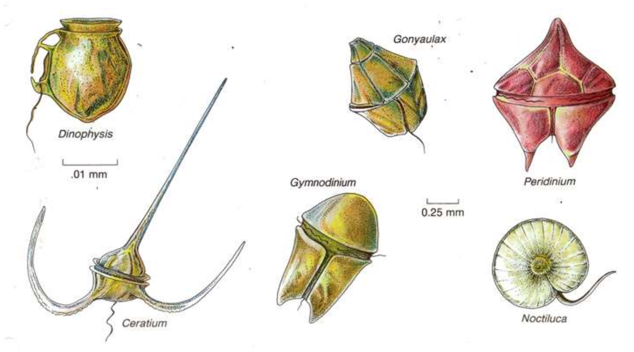
> A large range of size classes (1-2,000 μm)

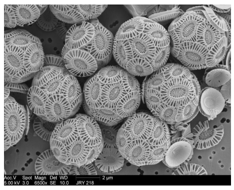
> Have different nutrient requirements according to cell size

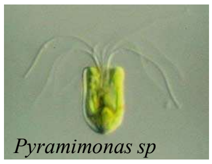
> Taxonomic and functional diversity

6

Flagellates swim towards better conditions of light and nutrients



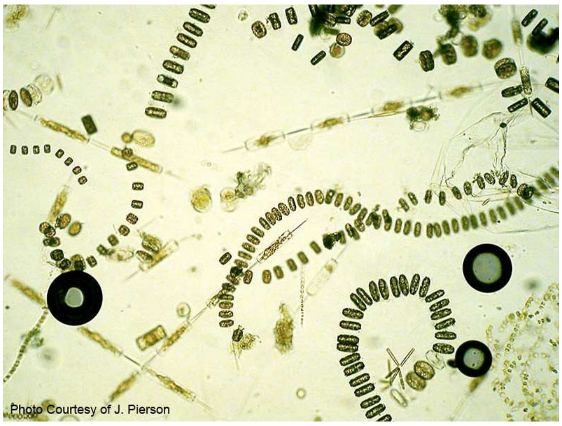


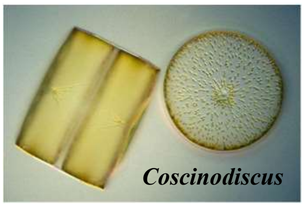


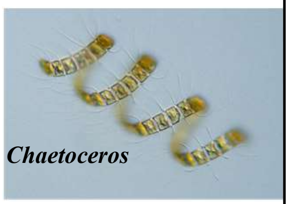
Coccolitophorids

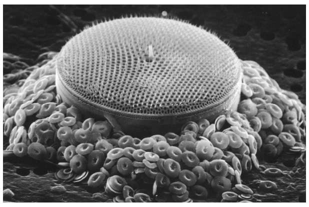
7

The larger and heavy diatoms – they sink fast









They are imobile and their Silica wall give them enough ballast to sink faster downwards. They dominate in the most productive áreas and are recycled in deep layers. Hence they lead the vertical flux of Carbom in the oceans

8

8

Nutrients control phytoplankton growth according to the Liebig´s Law (1840)

"The scarcest nutrient limits crop growth"

The Redfield Ratio (1934)

C : N : P : Fe

(106 : 16 : 1 : 0.002 by atoms)

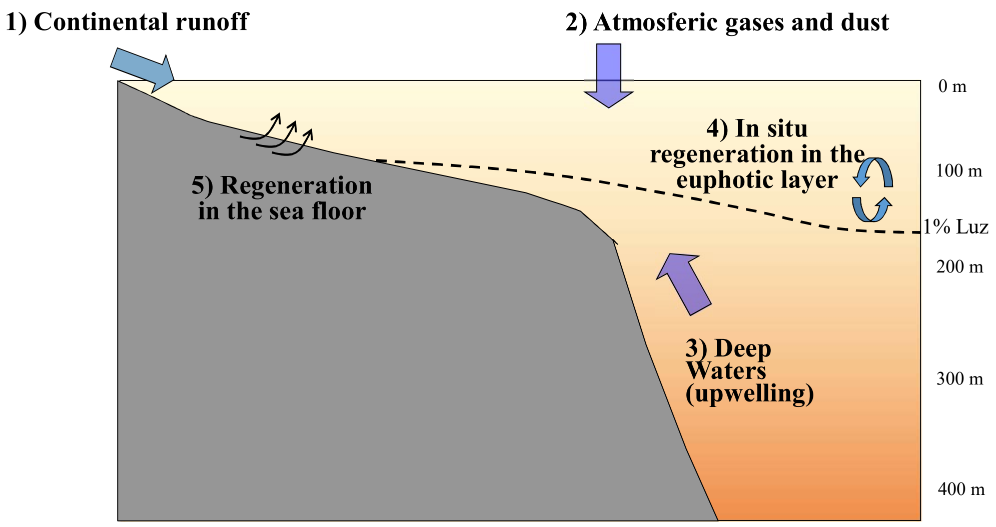
Therefore

If N:P>16 ➔ P is limiting the growth

If N:P<16 ➔ N is limiting the growth

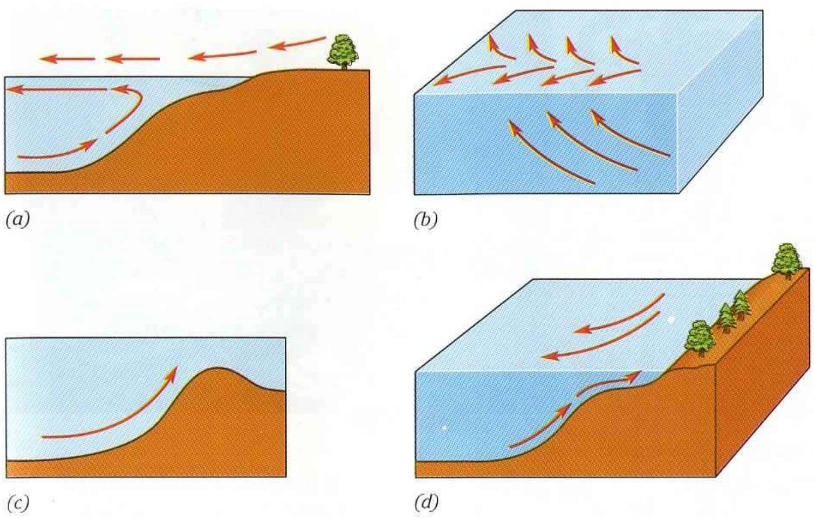
9

Nutrients inputs to the euphotic zone



10

Mass fertilization of surface waters by physical processes



Concentration of dissolved elements in seawater

Parts per Thousand	Parts per Million	Parts per Billion
19.3	19,300	19,300,000
10.7	10,700	10,700,000
2.7	2,700	2,700,000
1.3	1,300	1,300,000
0.09	90	90,000
0.014	14	14,000
0.005	5	5,000
0.003	3	3,000
0.0005	0.5	500
0.00007	0.07	70
0.000060	0.060	60
0.000010	0.010	10
0.000002	0.002	2
0.00000003	0.00003	0.03
0.00000003	0.00003	0.03

salts

Cl
Na
SO4
Mg
Ca
K
etc

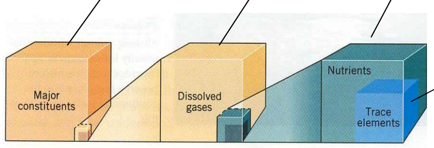
gases

N_2
O_2
CO_2

NO_3
PO_4
SiO_4

Fe
Mo
Zn

why [Fe] is so low in the ocean ?



Main sources of iron to the marine ecosystem

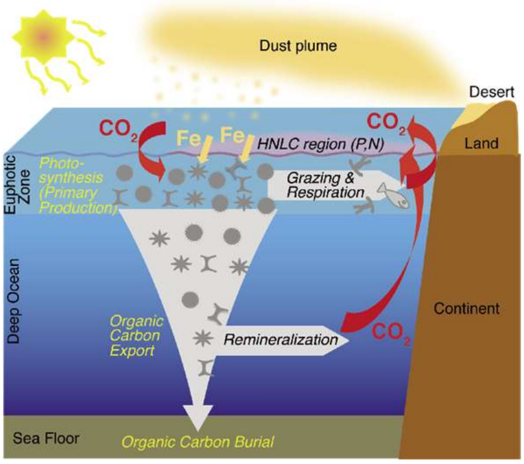
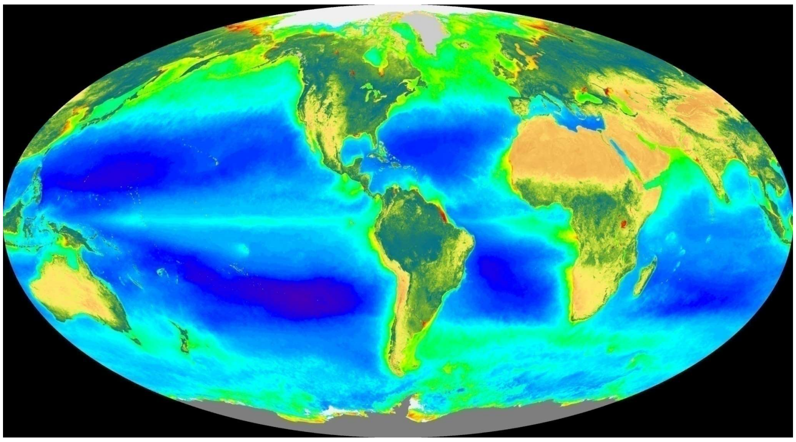


Image: Alfredo Martínez-García1 and Gisela Winckler
PAGES MAGAZINE · VOLUME 22 · NO 2 · OctObEr 2014

13

Global distribution of surface chlorophyll



Regional differences due to hydrodynamic processes
(vertical turbulence vs physical stratification)

14

Ocean surface temperature

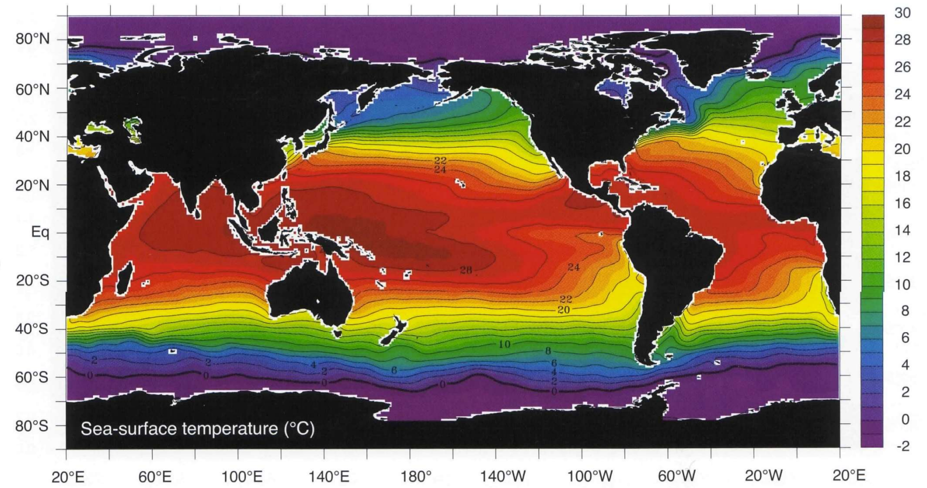
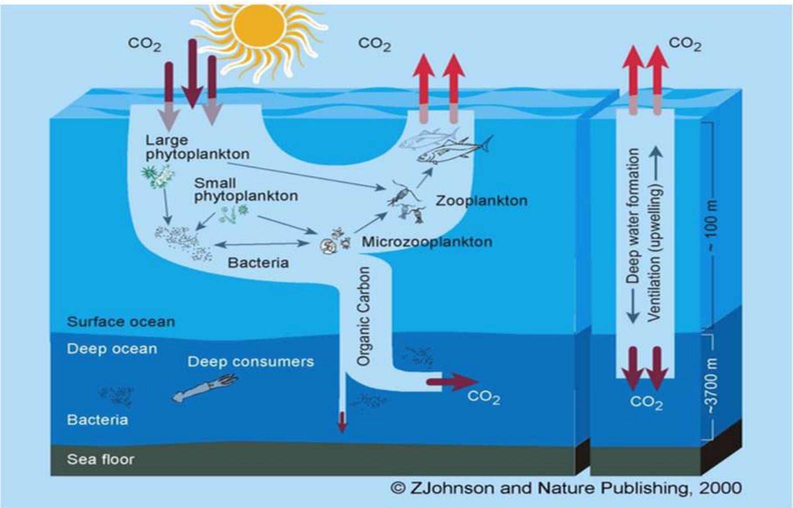


Image: Gruber & Sarmiento 2005

15

The ocean Carbom flux
(Carbom residence varies according to depth)



Source: Strong, A.L., Cullen, J.J. & Chisholm, S.W. (2009). Ocean Fertlization, Science, Policy, and Commerce, Oceanography, Vol. 22, No. 3, pp. 236-261.

16

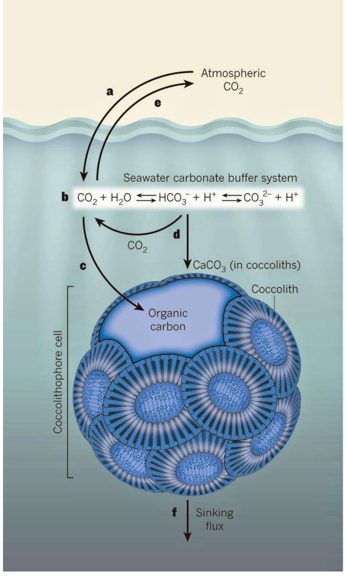
Coccolitophorids are important for the "chemical carbom pump"

Involved in short- and long-term carbom cycling

Short term - CaCO3 fixation depends on the uptake of Ca e CO2 as Bicarbonate through the equation

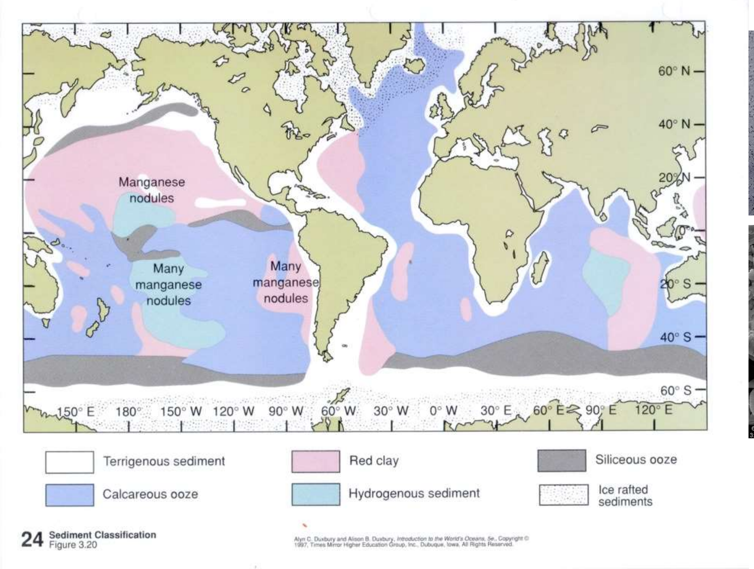
$Ca^{2+} + 2HCO_3^- \longleftrightarrow CaCO_3 + CO_2 + H_2O$
(1 mol of CO2 is released back to water)

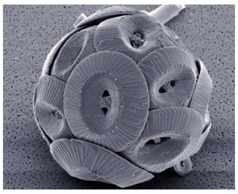
Long term – For calcification 2 atoms of C is needed and one of them may sediment to deep ocean floor.



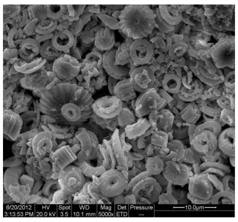
17

Mineral composition of the ocean floor – 50% are coccolitophorid scales of CaCO3





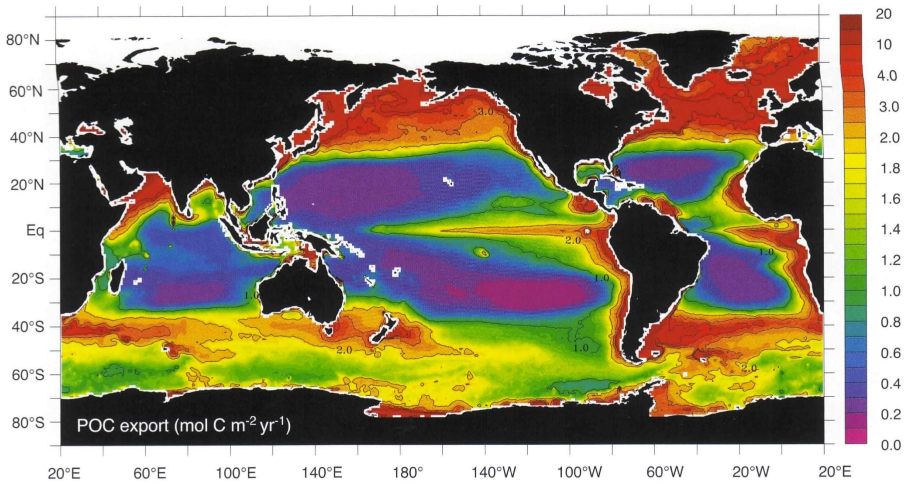
E. huxleyi



CaCO3 scales of cocolitophorids

18

Estimates of Carbon export to deep layers of the global ocean



19

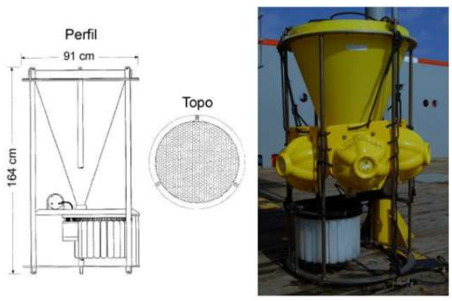


Figura 2: Desenho esquemático da armadilha de sedimento Mc Lane (Fonte: http://www.mclanelabs.com, acesso em maio\2016), e instalação da armadilha de sedimento em novembro de 2012. Fonte: Acervo pessoal.

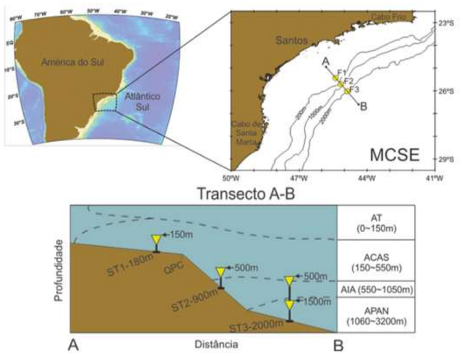


Figura 3: Localização dos fundeios na Margem Continental Sudeste (MCSE); posicionamento das armadilhas de sedimento na coluna de água e respectiva estrutura hidrográfica, segundo Stramma & England (1999).

$$fluxo\ de\ COP\ (ou\ NOP)(mg * m^{-2} * dia^{-1}) = \frac{(Ca-Cb)*VT}{Vf*A*T}$$ (Equação 4);

20

Surface concentration of Phosphate

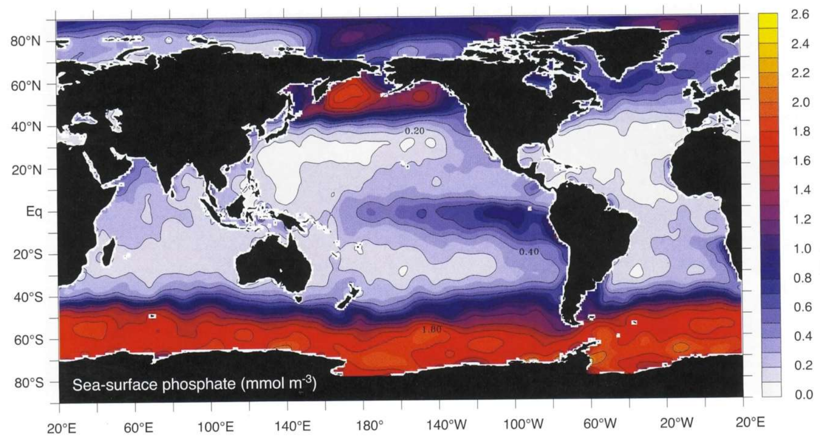


Image: Gruber & Sarmiento 2005

21

Surface concentration of Silicate

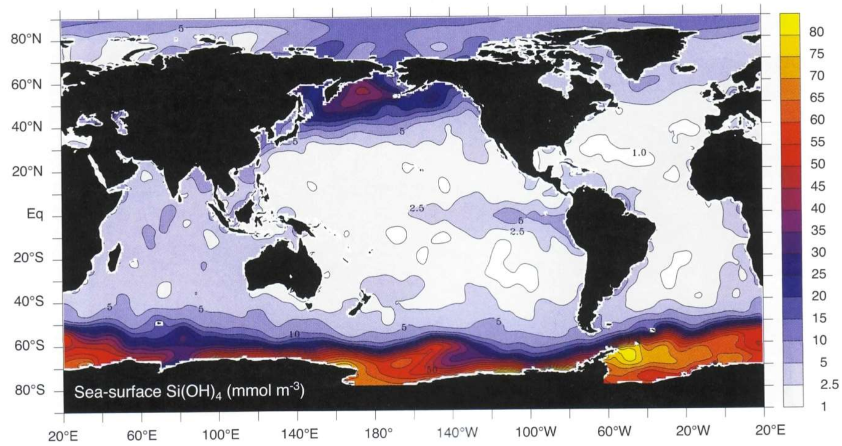


Image: Gruber & Sarmiento 2005

22

Surface concentration of nitrate

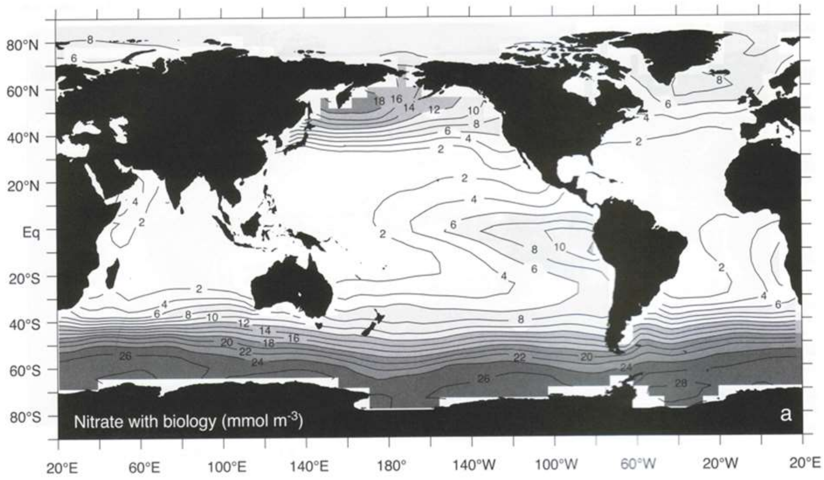
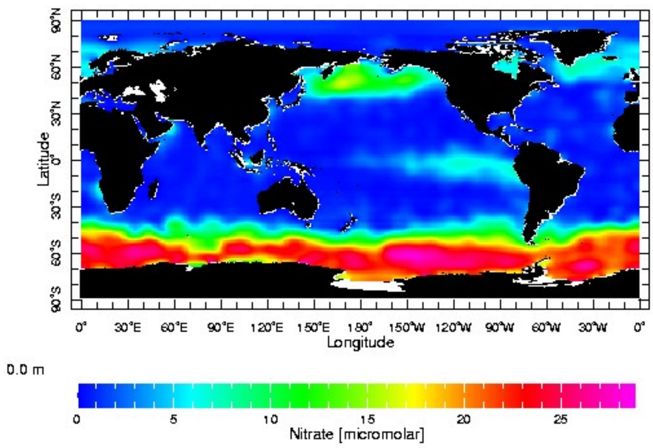


Image: Gruber & Sarmiento 2005

23

There are 3 oceanic areas where atmospheric inputs of iron is not suficient to use all macronutrients available



What are the natural sources of iron to the oceans?

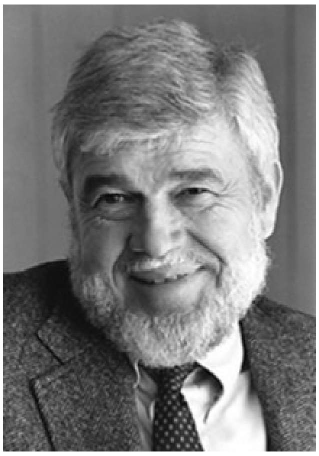
Image: https://schmidtocean.org/cruise-log-post/pumping-iron/

24

"Give me half a tanker of iron and I'll give you the next ice age"

- The meaning and controversies of the "iron hypothesis"

The pioneer Martin´s bottle experiment triggered the debate



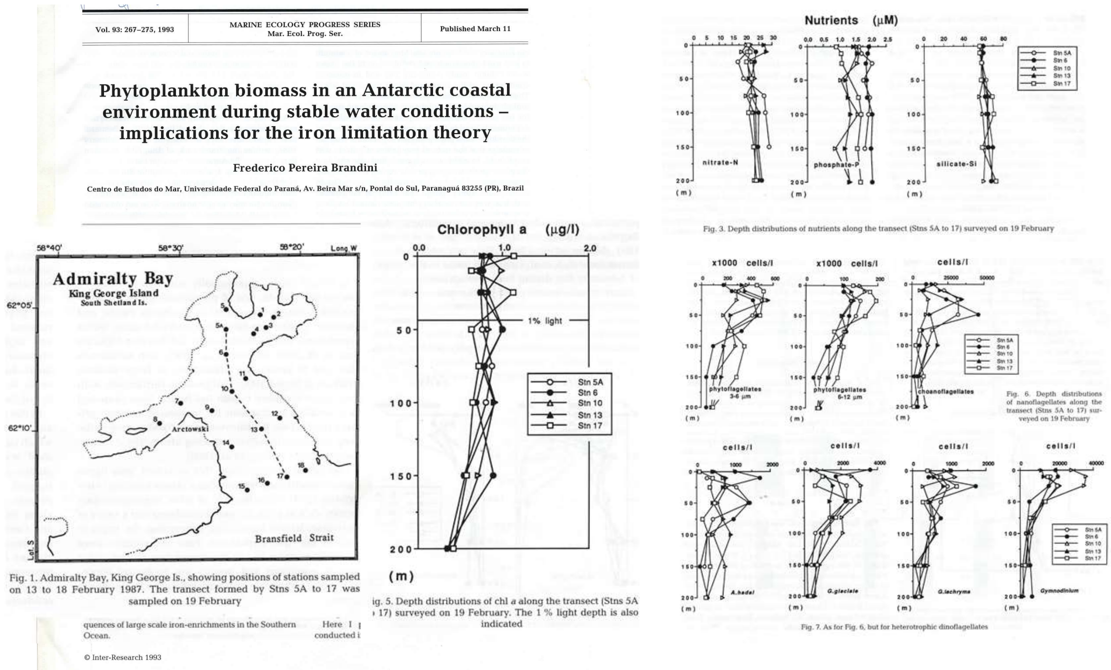
John Martin

25

The reaction of the oceanographic academic community to Martin´s hypothesis?

- Grazing or iron limitation?
- Critics about results obtained in bottle experiments ➔ Large scale experiments were necessary ➔ in 1993 the first iron fertilization off Galapagos ➔ 0,5 tonnes of iron in 5 nm2 patch and 3x more chlorophyll a week later
- More critics *"fertilizing the ocean would be treating the symptom, not the cause, of global warming!"*

26


Vol. 93: 267–275, 1993 MARINE ECOLOGY PROGRESS SERIES Mar. Ecol. Prog. Ser. Published March 11

Phytoplankton biomass in an Antarctic coastal environment during stable water conditions – implications for the iron limitation theory

Frederico Pereira Brandini

Centro de Estudos do Mar, Universidade Federal do Paraná, Av. Beira Mar s/n, Pontal do Sul, Paranaguá 83255 (PR), Brazil

Fig. 1. Admiralty Bay, King George Is., showing positions of stations sampled on 13 to 18 February 1987. The transect formed by Stns 5A to 17 was sampled on 19 February

Fig. 5. Depth distributions of chl a along the transect (Stns 5A to 17) surveyed on 19 February. The 1 % light depth is also indicated

Fig. 3. Depth distributions of nutrients along the transect (Stns 5A to 17) surveyed on 19 February

Fig. 6. Depth distributions of nanoflagellates along the transect (Stns 5A to 17) surveyed on 19 February

Fig. 7. As for Fig. 6, but for heterotrophic dinoflagellates

© Inter-Research 1993

27

J. Phycol. **36,** 1096–1102 (2000)

COMBINED EFFECTS OF TEMPERATURE AND IRON ON THE GROWTH AND PHYSIOLOGY OF THE MARINE DIATOM *PHAEODACTYLUM TRICORNUTUM* (BACILLARIOPHYCEAE)[1]

Isao Kudo,[2] Makiko Miyamoto, Yoshifumi Noiri, and Yoshiaki Maita

Graduate School of Fisheries Science, Hokkaido University, Hakodate, Japan 041-8611

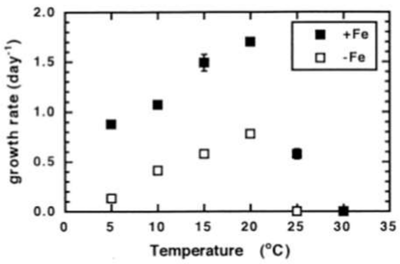
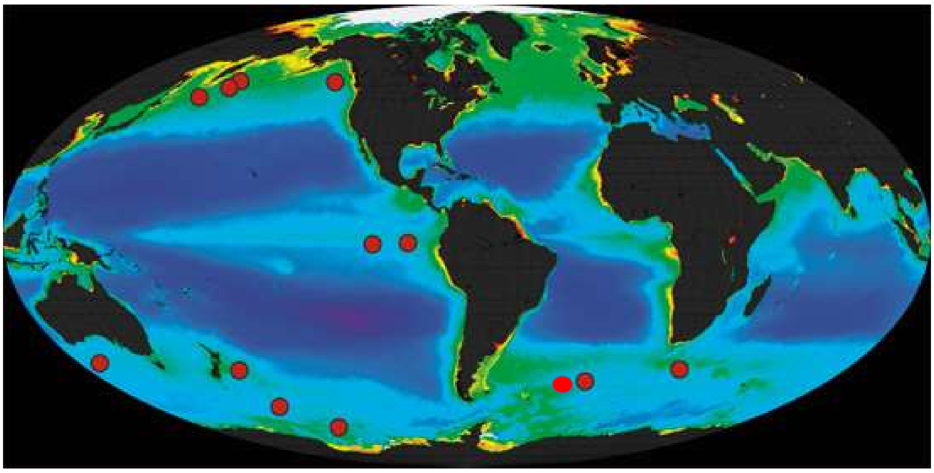


FIG. 1. Change in growth rate with growth temperature under Fe-replete (+Fe) and Fe-stressed (−Fe) conditions. Error bars represent ± 1 SE (n = 3) and are not visible when smaller than the symbol.

Alem da composição de enzimas fotossintéticas o *Fe* entra na composição de enzimas necessárias para a absorção de sílica pelas diatomáceas
Por isso elas tendem a dominar nos experimentos de enriquecimento com *Fe*

28

13 small-scale (40-300 Km2) experiments were made since 1993



29

Logistics and sampling during iron fertillization experiment in the Gulf of Alaska

Experimental ocean fertilization using ferrous sulphate on UK-GermanFeeP study 2004 – 10 tons of iron sulphate

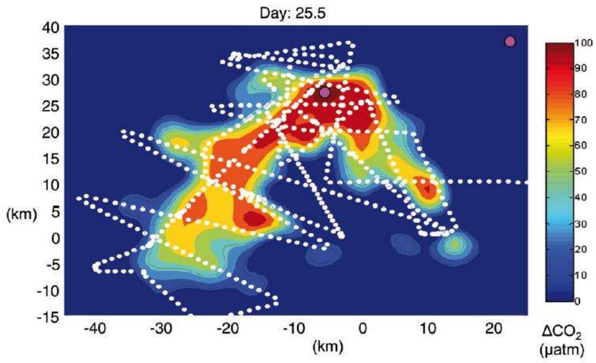
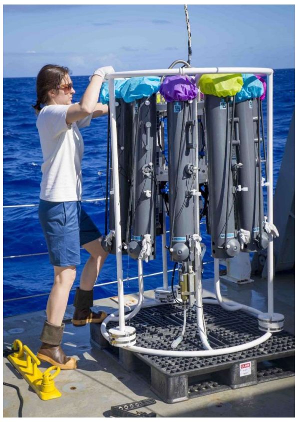


Image: Alfredo Martínez-García1 and Gisela Winckler PAGES MAGAZINE · VOLUME 22 · NO 2 · October 2014

30

Sampling techniques of experimental ocean *Fe* fertilization



Trace Metal CTD/Rosette sampler to analyse iron in seawater (source: Pamela Barret. Schmidt Ocean Institute https://schmidtocean.org/cruise-log-post/pumping-iron/

31

Results were not consistent

1) Turbulent mixing, lateral advection, light availability, and other in situ conditions

2) Technical dificulties

- iron solubility in sea water → 75% of the Fe may be lost
- dispersion of new biomass → it would not happen in terrestrial habitats
- Diferences in the availability of other nutrientes (N, P & Si)

32

...except for the following general conclusions

- Iron addition always increased phytoplankton biomass
- Results varied from 2-25 times more chlorophyll than in control areas
- Greater effect in shallow mixed layers due to more light availability
- In most experiments phytoplankton composition shifted from smaller towards larger cells, usually diatoms
- Diatom species varied between locations and experiments
- Bacterial biomass increased by 2-15 times
- Small grazers also increase in some experiments
- Experiments did no last long enough to check for large grazers
- Unable to check the effects on higher trophic levels

33

Modelling the impact of large-scale experiments

- Increase the flux of CO2 into the ocean due to lowering the pCO2
- May increase ocean acidification – unpredictable effects on marine biodiversity
- The increase of organic matter in deep layers demand more oxygen causing anoxy or increasing the minimum oxygen zone - unpredictable effects on marine biodiversity
- Most experiments detected higher [DMS] that may promote cloud formation. Modelling extrapolation suggests fertilization of 2% of the Southern Ocean could cause a 2 degree decrease of mean air temperature.

34

Modelling the impact of large-scale experiments

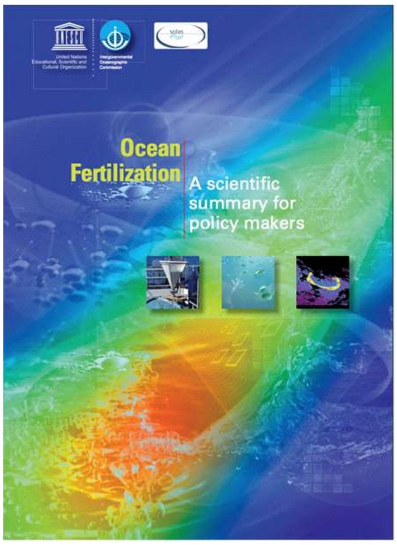
- Potential to increase the occurrence of Harmful Algal Blooms
- Far-field effects: deficit of macro-nutrients in islands or other coastal areas offseting the CO_2 taken up in the experimental location.
- Far-field “nutrient robbing”: affects regional fisheries.
- On the other hand the increase of [nutrient] in deep waters due to local vertical export of more organic matter may increase even more the productivity in remote upwelling zones.

35

How effective is ocean iron fertilization to control global warming

- Most experiments confirmed but part of the iron hypothesis ➔ surface carbom biomass increase
- But to be effective it must reach layers below 500 m to keep the residence of the Carbom uptaken for approximately 100 years (few experiments proved this exportation)
- To decrease global warming experiments will have to be of a much larger scales in terms of space (thousands of km^2) and fertilization time (for decades)
- In Brazilian tropical waters large scale iron fertilization should be ineffective due to lack of macronutrients. Artificial upwelling may effectively take up atmospheric CO_2 by increasing primary production though not to the scale necessary to control global warming

36



FURTHER reading

Ocean fertilization: general

Gnanadesikan A & Marinov I (2008) Export is not enough: nutrient cycling and carbon sequestration. *Marine Ecology Progress Series*, 364, 289-94

Gussow K, Proelss A, Oschlies A, Rehdanz K & Rickels W (2010) Ocean iron fertilization: Why further research is needed. *Marine Policy* 34, 911-918

Lampitt RS and 11 others (2008) Ocean fertilization: a potential means of geoengineering? *Phil Trans Roy Soc A*, 366 (1882) 3919-45

Secretariat of the Convention on Biological Diversity (2009) *Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity*. Montreal, Tech Ser No. 45, 53pp

Strong AL, Cullen JJ & Chisholm SW (2009) Ocean fertilization. Science, policy and commerce. *Oceanography* 22, 236-61

Micronutrients: external additions (iron)

Aumont O & Bopp L (2006) Globalizing results from ocean in situ iron fertilization studies. *Global Biogeochemical Cycles* 20, GB2017, doi:10.1029/2005GB002591

Boyd PW and 22 others (2007) Mesoscale iron enrichment experiments 1993-2005: synthesis and future directions. *Science* 315, 5812, 612-7

Cao L & Caldeira K (2010) Can ocean iron fertilization mitigate ocean acidification? *Climatic Change* 99, 303-11

Cullen JJ & Boyd PW (2008) Predicting and verifying the intended and unintended consequences of large-scale ocean iron fertilization. *Marine Ecology Progress Series*, 364, 295-301

de Baar HJW, Gerringa LJA, Laan P & Timmermans KR (2007) Efficiency of carbon removal per added iron in ocean iron fertilization. *Marine Ecology Progress Series*, 364, 269-82

Denman K (2008) Climate change, ocean processes and ocean iron fertilization. *Marine Ecology Progress Series*, 364, 219-25

Law CS (2008) Predicting and monitoring the effects of large-scale ocean iron fertilization on marine trace gas emissions. *Marine Ecology Progress Series*, 364, 283-8

Also other papers in theme section of *Marine Ecology Progress Series* (2008); vol 364, 213-309

Macronutrients: external additions (phosphorus and nitrogen)

Glibert PM and 56 others (2008) Ocean urea fertilization for carbon credits poses high ecological risks. *Marine Pollution Bulletin* 56, 1049-56

Krom M and 9 others (2005) Summary and overview of the CYCLOPS P addition Lagrangian experiment in the Eastern Mediterranean. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52, 3090-108

Matear RJ & Elliot B (2004) Enhancement of oceanic uptake of anthropogenic CO2 by macronutrient fertilisation. *J Geophysical Research* 109 (C04001) doi: 10.10129/2000JC000321

Mayo-Ramsay J (2010) Environmental, legal and social implications of ocean urea fertilization: Sulu sea example. *Marine Policy* 34, 831-35

Macronutrients: enhanced recycling (artificial upwelling)

Oschlies A, Pahlow M, Yool A & Matear RJ (2010) Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters* 37, L04701, doi:10.1029/2009GL041961

White A, Björkman K, Grabowski E, Letelier R, Poulos S, Watkins B & Karl D (2010) An open ocean trial of controlled upwelling using wave pump technology. *J Atmospheric & Oceanic Technology* 27, 385-96

Yool A, Shepherd JG, Bryden HL & Oschlies A (2009) Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide. *J Geophysical Research - Oceans* 114, doi C08009.

Policy and legislative aspects

Bertram C (2010) Ocean iron fertilization in the context of the Kyoto protocol and the post-Kyoto process. *Energy Policy* 38, 1130-9

Blackstock JJ & Long JCS (2010) The politics of geoengineering. *Science* 327 (5965), 527

Leinen M (2008) Building relationships between scientists and business in ocean iron fertilization. *Marine Ecology Progress Series*, 364, 251-6

LC/LP 2009 Technical Working Group and Legal Working Group reports at www.imo.org/includes/blastDataOnly.asp/data_id%3D25080/5.pdf and www.imo.org/includes/blastDataOnly.asp/data_id%3D25078/5.pdf

Geoengineering: general

Boyd, PW (2008) Ranking geo-engineering schemes. *Nature Geoscience* 1, 722-4

Lenton T & Vaughan N (2009) The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry & Physics* 9, 5539-61

Ross A & Matthews HD (2009) Climate engineering and the risk of rapid climate change. *Environmental Research Letters* 4, 045103 doi: 10.1088/1748-9326/4/4/045103

Royal Society (2009) *Geoengineering the climate: science, governance and uncertainty*. RS Policy Document 10/09

Main commercial interests

Atmocean Inc (wave-driven ocean upwelling system) www.atmocean.com

Ocean Nourishment Corporation Pty Ltd (macronutrient additions to enhance fish stocks and carbon sinks) www.oceannourishment.com

Climos (potential application of ocean iron fertilization) www.climos.com

37

Further Reading

Secretariat of the Convention on Biological Diversity (2009). Scientific Synthesis of the Impacts of Ocean Fertilization on Marine Biodiversity. Montreal, Technical Series No. 45, 53 pages (available in https://www.cbd.int/doc/publications/cbd-ts-45-en.pdf)

Thank you
Obrigado

38

Thank you
Obrigado

39