CO_2 sequestration in the ocean

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Alfred-Wegener-Institut für Polar- und Meeresforschung
in der Helmholtz-Gemeinschaft

Foto: L. Tadday

ERCA, Grenoble 3 February 2010

CO_2 emissions: A large scale geophysical experiment (Revelle & Suess, 1957)

"Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

Roger Revelle

Hans Suess in 1972

The 2°C warming target
CO_2 emissions: less than 205 Gt C until 2050

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Greenhouse-gas emission targets for limiting global warming to 2 °C

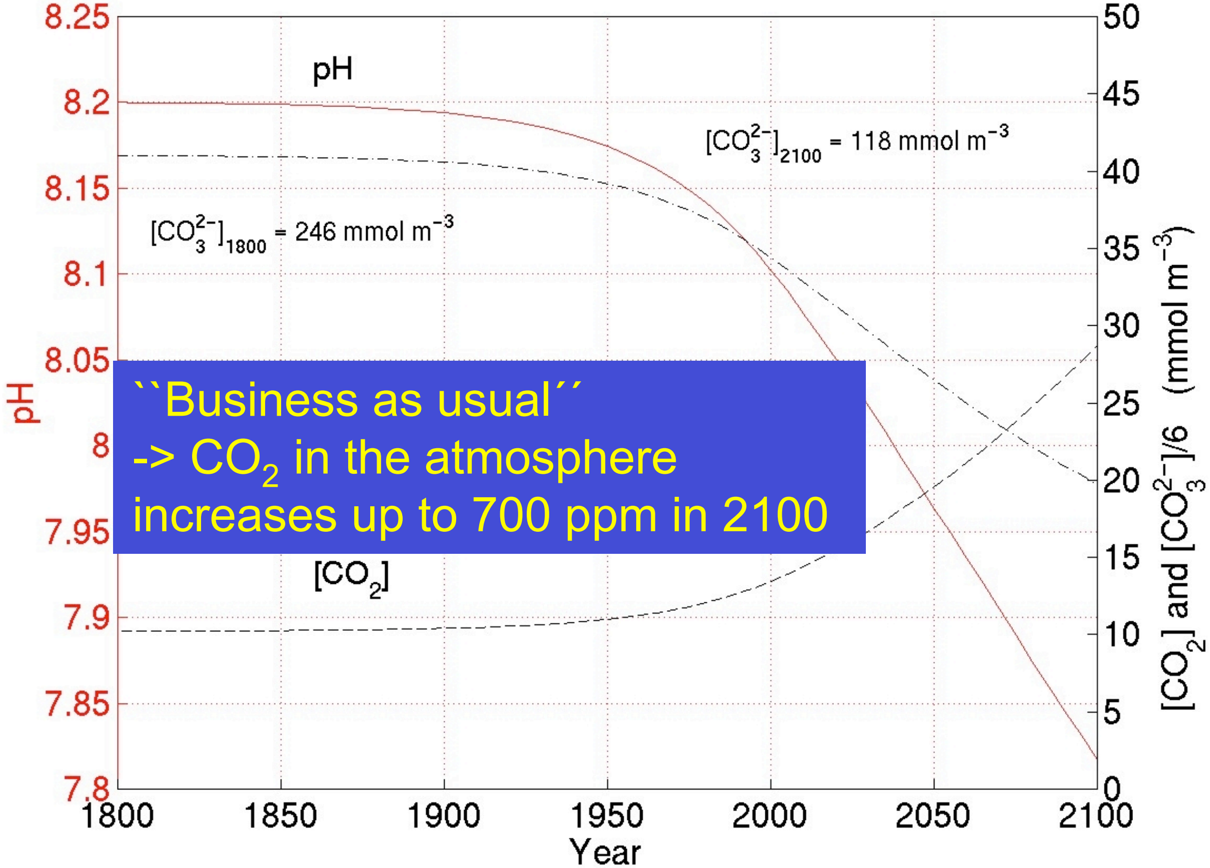
Malte Meinshausen[1], Nicolai Meinshausen[2], William Hare[1,3], Sarah C. B. Raper[4], Katja Frieler[1], Reto Knutti[5], David J. Frame[6,7] & Myles R. Allen[7]

Limiting cumulative CO_2 emissions over 2000–50 to 1,000 Gt CO_2 yields a 25% probability of warming exceeding 2 °C—and a limit of 1,440 Gt CO_2 yields a 50% probability—given a representative estimate of the distribution of climate system properties.

Between 2000 and 2050: < 1000 Gt CO_2 = 273 Gt C
Between 2010 and 2050: < 750 Gt CO_2 = 205 Gt C
Current emission: ≈ 9 Gt C yr-1 -> ≈ 20 years

3.67 g CO_2 = 1 g C

It's not just warming: Ocean acidification



``Business as usual´´
-> CO_2 in the atmosphere increases up to 700 ppm in 2100

Wolf-Gladrow et al., Tellus, B51(2), 461-476, 1999.

Advantage for algae: higher CO_2 concentration

Problems for calcifying organisms: $CaCO_3$ dissolves at low pH

Physiology of marine organisms

Ecosystems: change in species assemblage & function

Significant decreases in ocean sound absorption -> noisier, whales

Limacina retroversa australis (pteropod, ca. 2 mm), Southern Ocean, aragonite ($CaCO_3$) (Foto: Wolf-Gladrow)

DON‘T BE HUMBLE!

Humble is a small town in Texas.
Enco: now they call themselves Exxon.
From Life Magazine 1962.

(thanks to Stephen Salter)

Outline

1. Motivation

2. The global carbon cycle

3. Approaches: ocean iron fertilization, silicate weathering, ...
   What is the potential? Will it be effective?

4. Final remarks

The Global Carbon Cycle: Preindustrial and in in the 1990s

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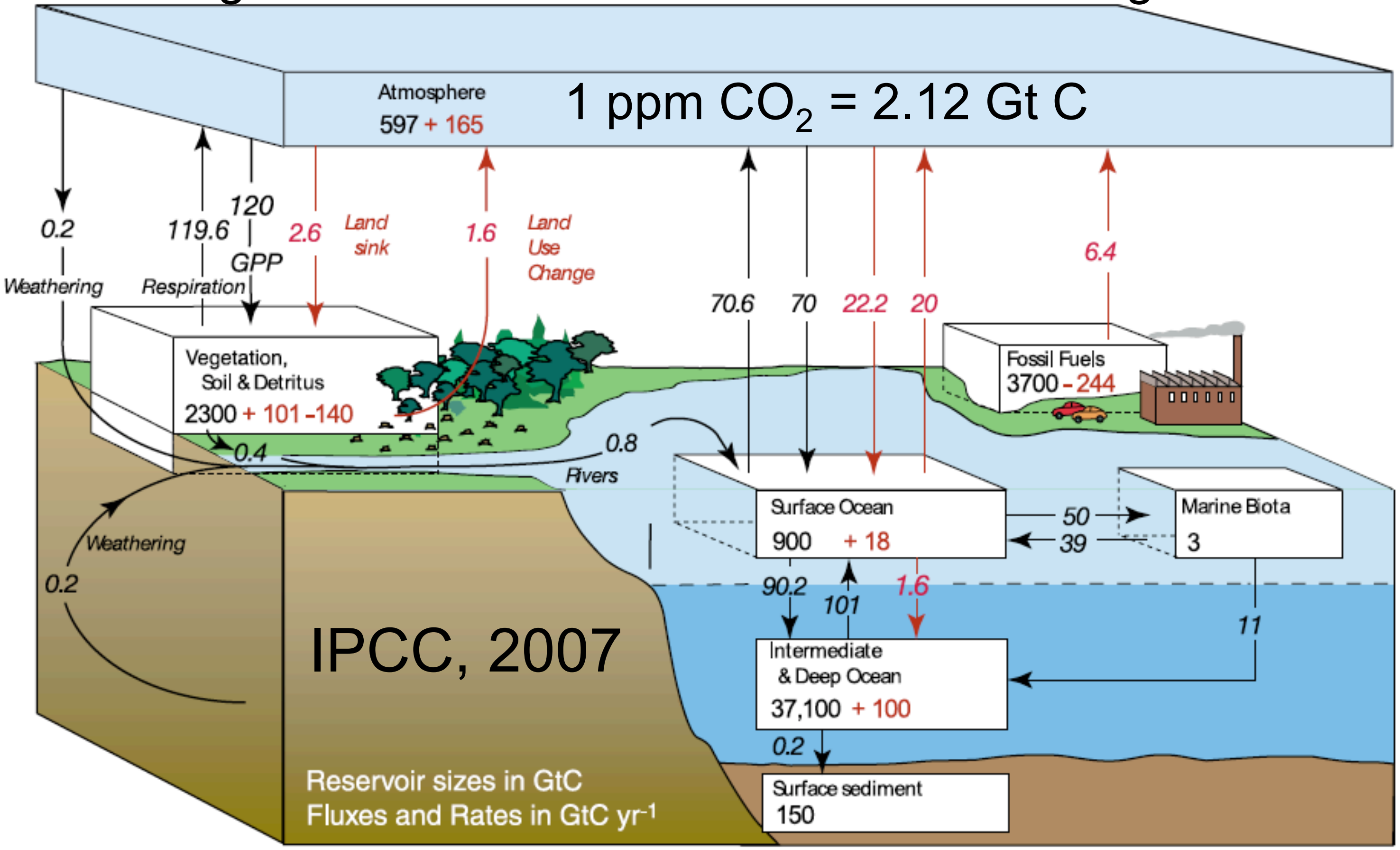
1 Pg C = 1 Gt C = 1 000 000 000 t C = 10^{15} g C

1 ppm CO_2 = 2.12 Gt C



3 active reservoirs: atmosphere, land biota & soils, ocean (= largest reservoir)

Natural fluxes are large (100 Pg C yr^{-1})

Anthropogenic CO_2 fluxes: different quality (not balanced)

3.67 g CO_2 = 1 g C

AWI

Why does CO_2 in the atmosphere-ocean system behave so much differently than O_2 or N_2?

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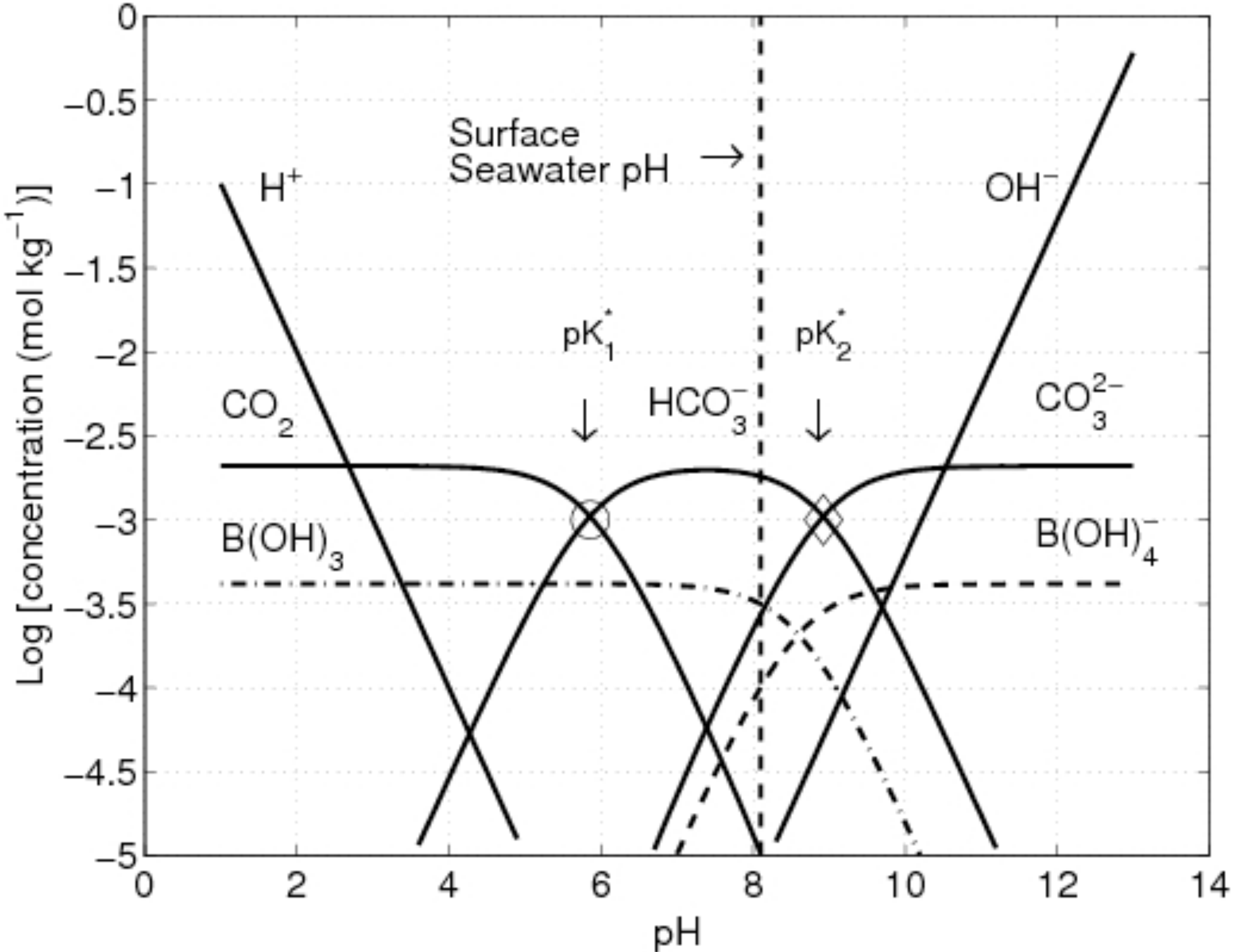
In contrast to N_2 and O_2 most C of the combined atmosphere-ocean system is dissolved in seawater. Why is CO_2 so different?

When CO_2 dissolves in seawater it reacts with water ($CO_2 + H_2O$) and forms H_2CO_3 (true carbonic acid) that dissociates into HCO_3^- (bicarbonate) and H^+ ('protons' in the slang of marine chemists).

-> Addition of CO_2 to the ocean leads to creation of H^+ und thus to ocean acidification ('the other CO_2 problem').

Bjerrum plot (Zeebe & Wolf-Gladrow, 2001)



Ocean acidification: shift to the left (lower pH) -> more CO_2, more HCO_3^-, less CO_3^{2-}

C in the ocean: in which form?

DIC = dissolved inorganic carbon = $[CO_2] + [HCO_3^-] + [CO_3^{2-}]$

= 98% of all C in the ocean

CO_2	dissolved gas, $CO_2(aq)$	1% of DIC	300 Pg C
HCO_3^-	bicarbonate	90% of DIC	34300 Pg C
CO_3^{2-}	carbonate ions	9% of DIC	2700 Pg C

DOC = dissolved organic carbon 700 Pg C

C in marine biota 3 Pg C

DIC distribution in the ocean

Takahashi, T. 1989. The carbon dioxide puzzle. Oceanus, 32: 22-29.

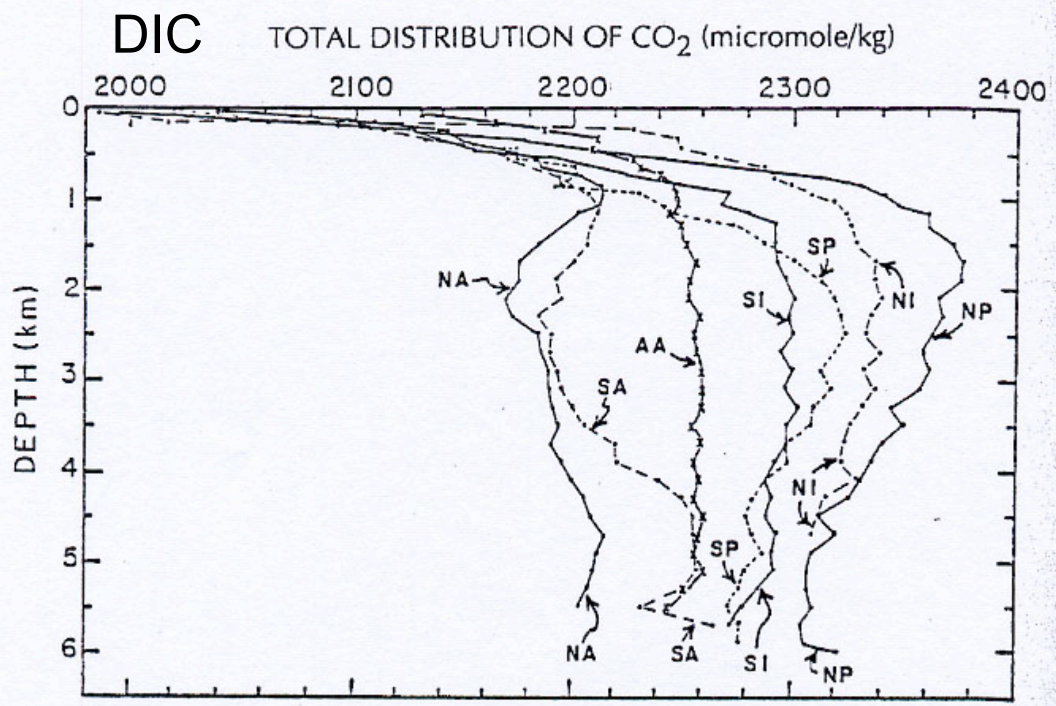


Figure 1. Depth distribution of the total CO_2 concentration in the global oceans. NA & SA = North & South Atlantic; NP and SP = North and South Pacific; NI and SI = North and South Indian Oceans; and AA = Antarctic ocean.

Inhomogeneous distribution: from < 2000 μmol kg^{-1} up to almost 2400 μmol kg^{-1} , i.e. 20% variation

1. Low concentrations in surface ocean.
2. Maxima at intermediate depths.
3. Increase from North Atlantic to Southern Ocean to North Pacific.

How to explain this distribution?

Which processes create inhomogeneous DIC distribution? I. Physical or solubility pump

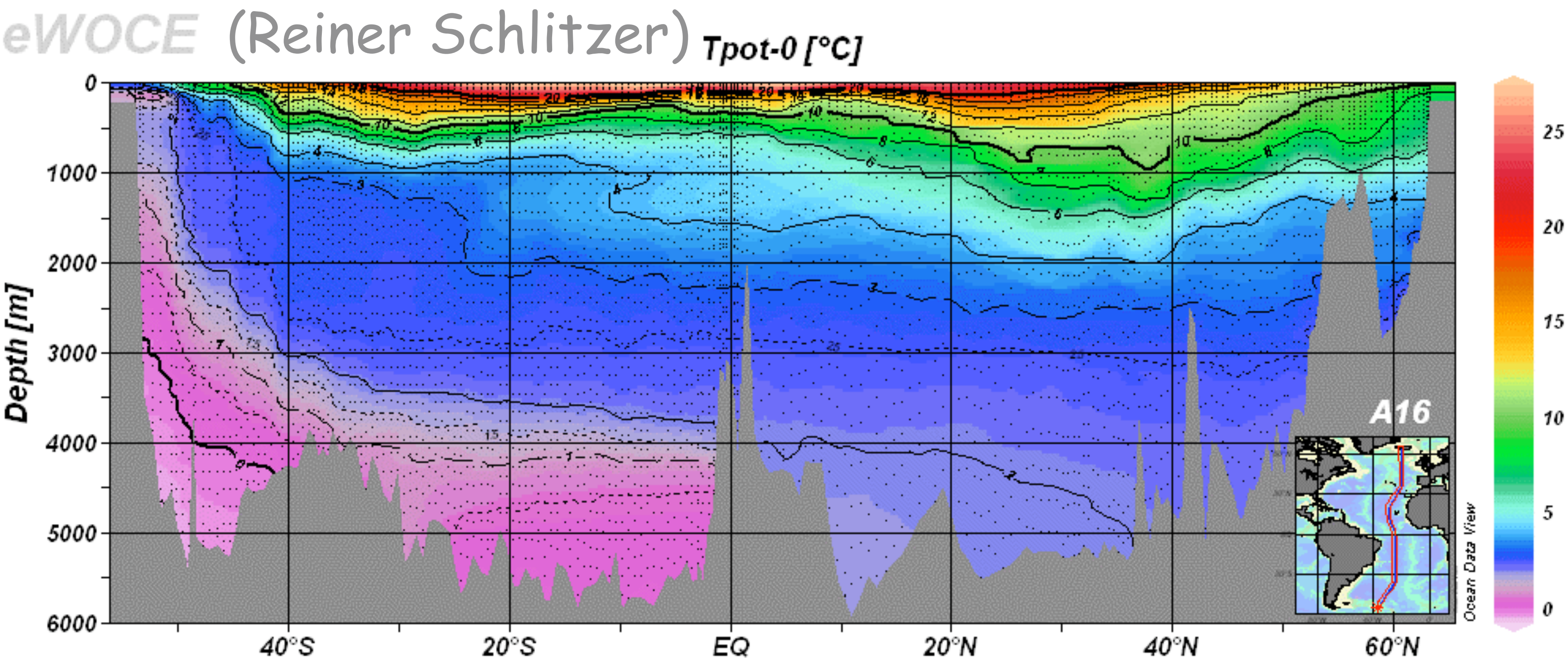
Mixing in the ocean (up to 1000 years) is much slower than in the atmosphere (1 year between hemispheres)

Pump: transport against the concentration gradient, i.e. from surface ocean to intermediate and deep layers.

1: Physical or solubility carbon pump:
The solubility of CO_2 is higher in cold than in warm water
-> more CO_2 and DIC in cold water
+ circulation: deep water formation in cold regions, deep ocean is cold and rich in DIC

Most of the ocean is cold

The warm water sphere is restricted to a thin surface layer.
... most of the ocean is cold (< 5°C) and rich in DIC



Which processes create inhomogeneous DIC distribution? II. Biological C pumps

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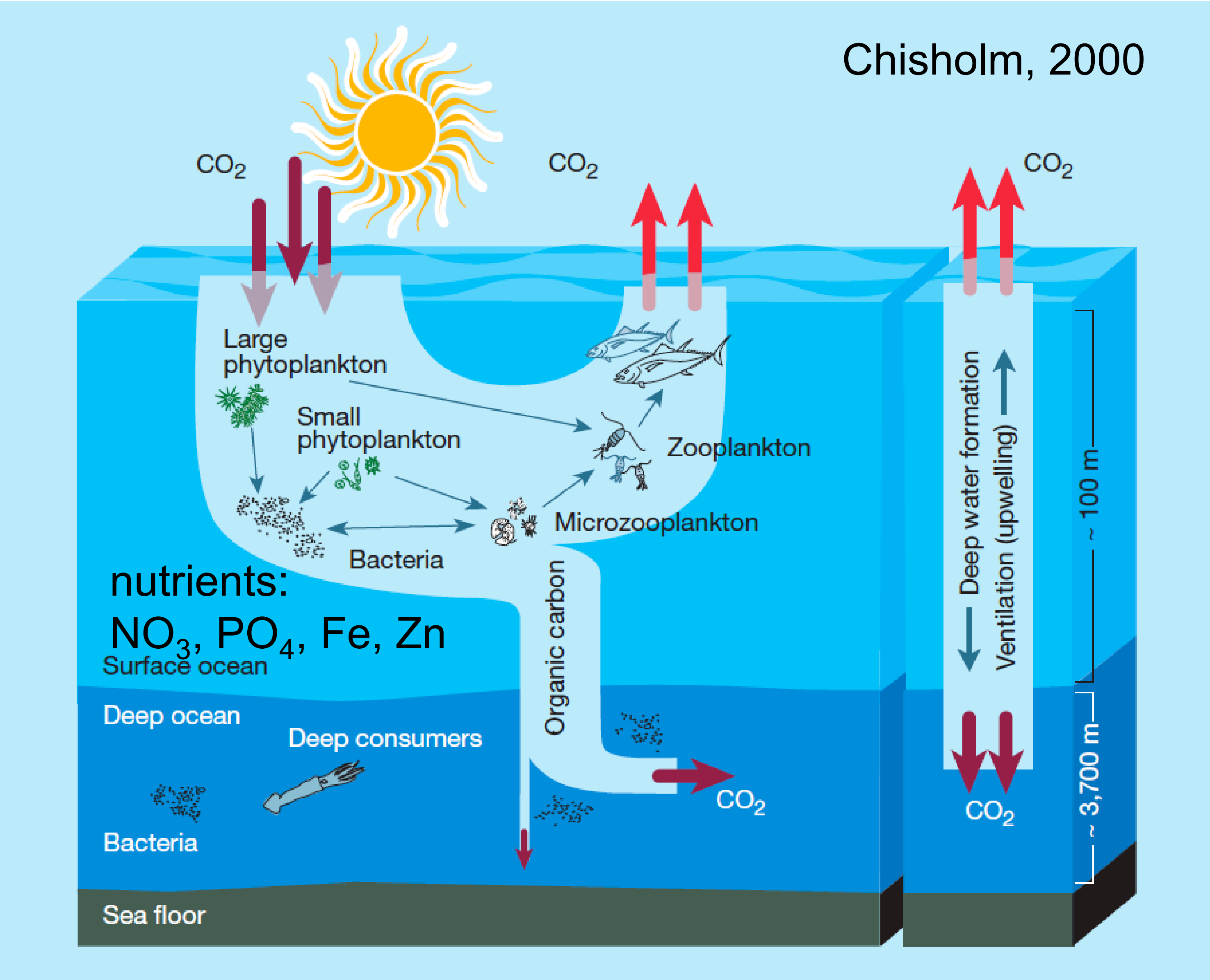
1. **Soft tissue pump**: production of organic material in the surface ocean by phytoplankton (microalgae, size 2-50 μm), transport (export) to deeper layers in the form of algal aggregates or faecal pellets and remineralisation (oxidation, release of CO_2) at depth by zooplankton and bacteria.

2. **Calcium carbonate ($CaCO_3$) pump**: production of $CaCO_3$ by coccolithophores (calcifiying microalgae), foraminifera (protozoa), pteropods (marine snails, 'butterflies of the sea'), export and dissolution at depth (release of DIC) or accumulation in sediments.

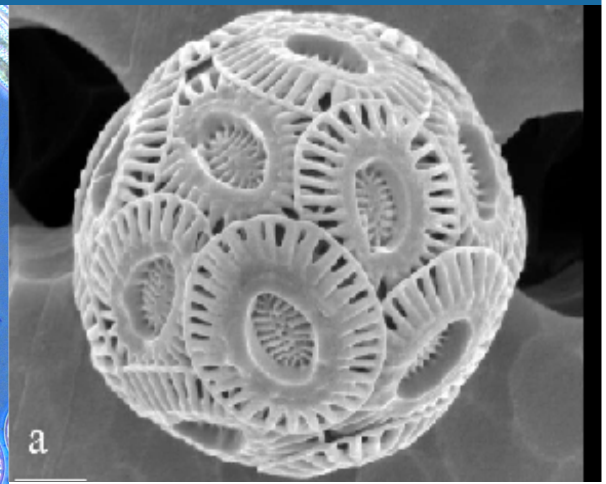
The biological pumps are complex and difficult to describe quantitatively (geochemists would be happy if one could ignore 'biology'). However, 75% of the vertical DIC gradient is due to the biological pumps.

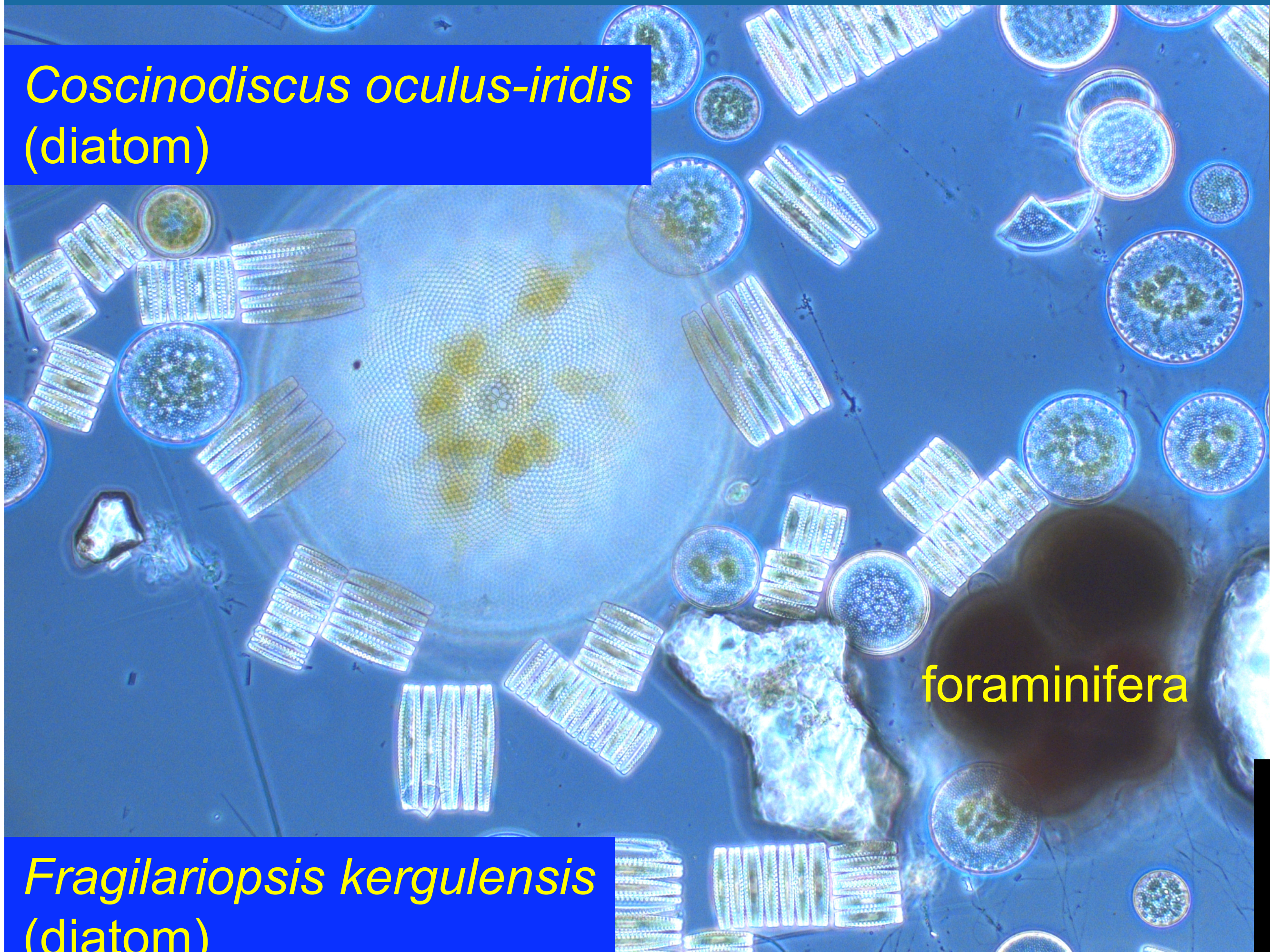
The carbon pumps



Biological C pumps: some of the key players!

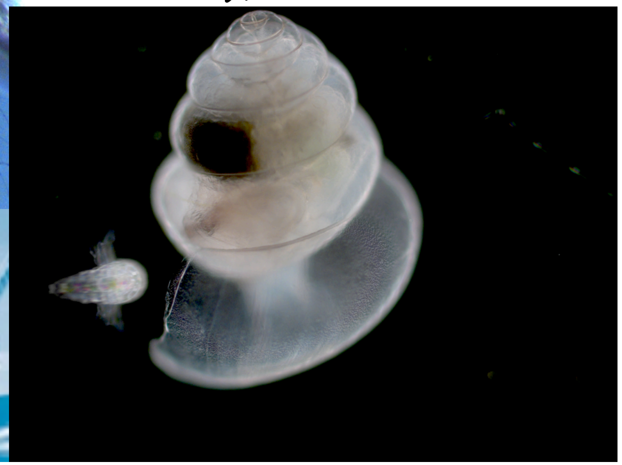
Emiliania huxleyi
(coccolithophore)



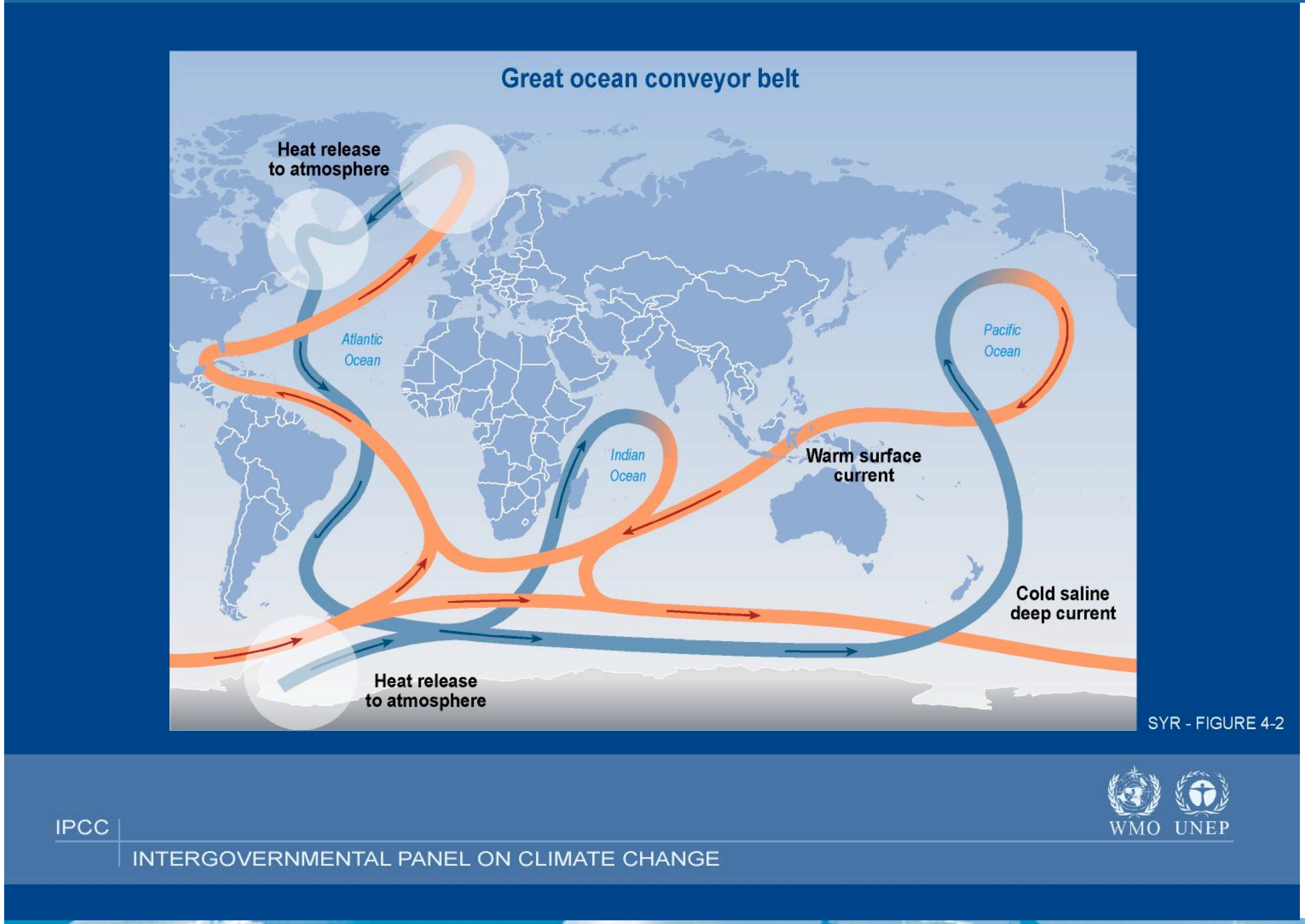


... and many more

Limacina retroversa australis (pteropod, ca. 2 mm),



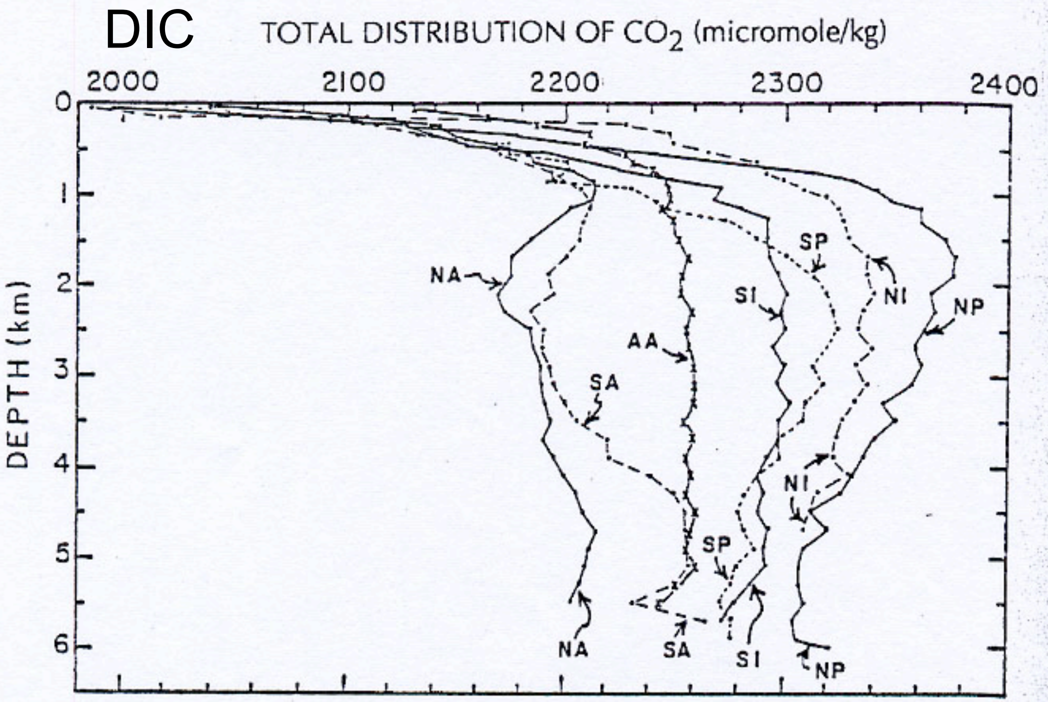
Which processes create inhomogeneous DIC distribution? Great ocean conveyor belt



Biological
C pumps
⇒
DIC at depth increases along the conveyor belt from the Atlantic to the Pacific

DIC distribution in the ocean

Takahashi, T. 1989. The carbon dioxide puzzle. Oceanus, 32: 22-29.



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1. Low concentrations in surface ocean.
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Total alkalinity

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TA ≈ proton acceptors - proton donors

$TA = [HCO_3^-] + 2\,[CO_3^{2-}] + [B(OH)^-] + [OH^-] - [H^+]$ + minor components

$= [Na^+] + 2\,[Mg^{2+}] + 2\,[Ca^{2+}] + 2\,[Sr^{2+}] + \ldots$

$- [Cl^-] - [Br^-] - [NO_3^-] - \ldots$

$- TPO_4 + TNH_3 - 2\,TSO_4$

total phosphate = $TPO_4 = [H_3PO_4] + [H_2PO_4^-] + [HPO_4^{2-}] + [PO_4^{3-}]$

CO_2 as a function of DIC & TA

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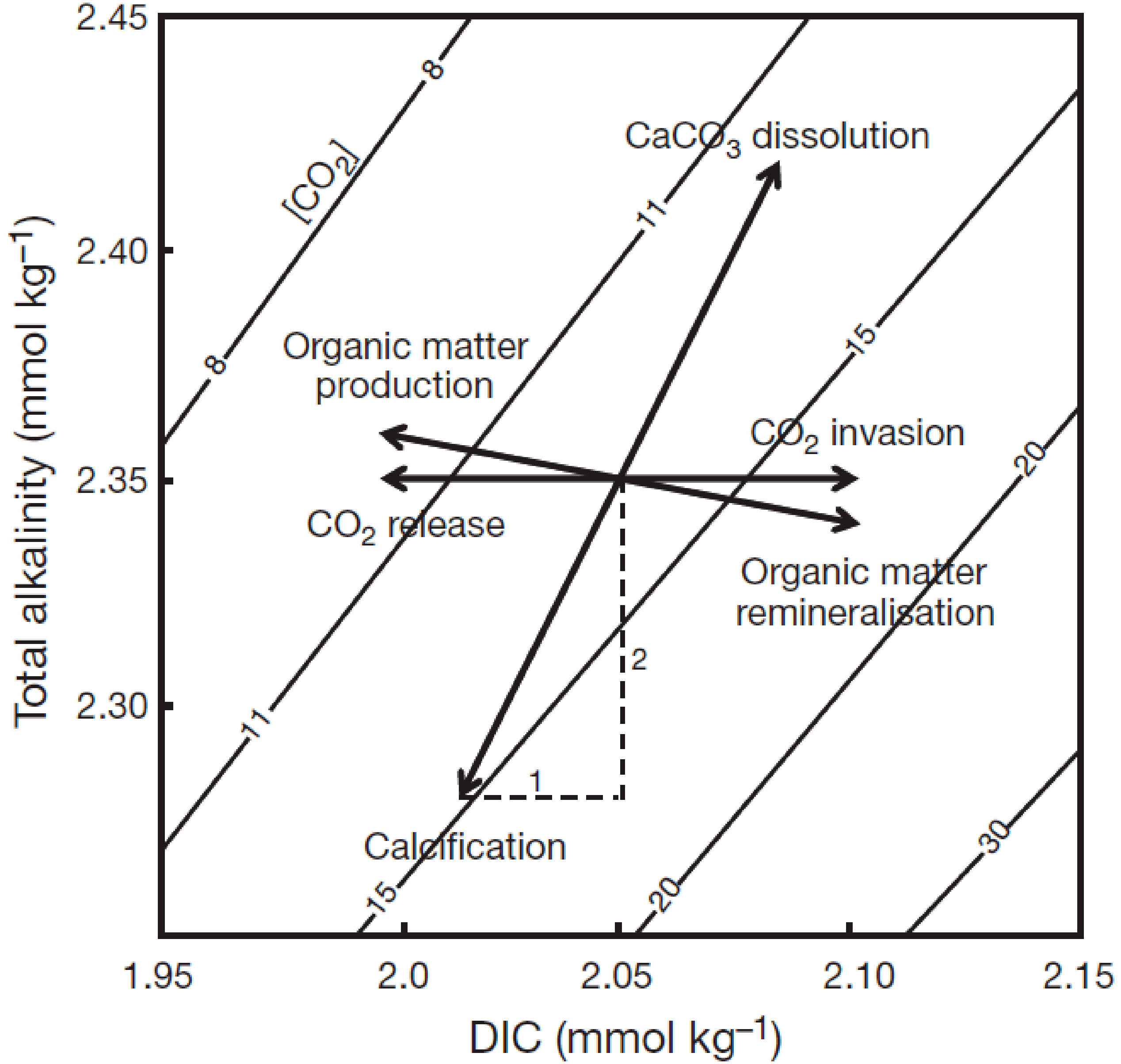

CO_2 sequestration in the ocean

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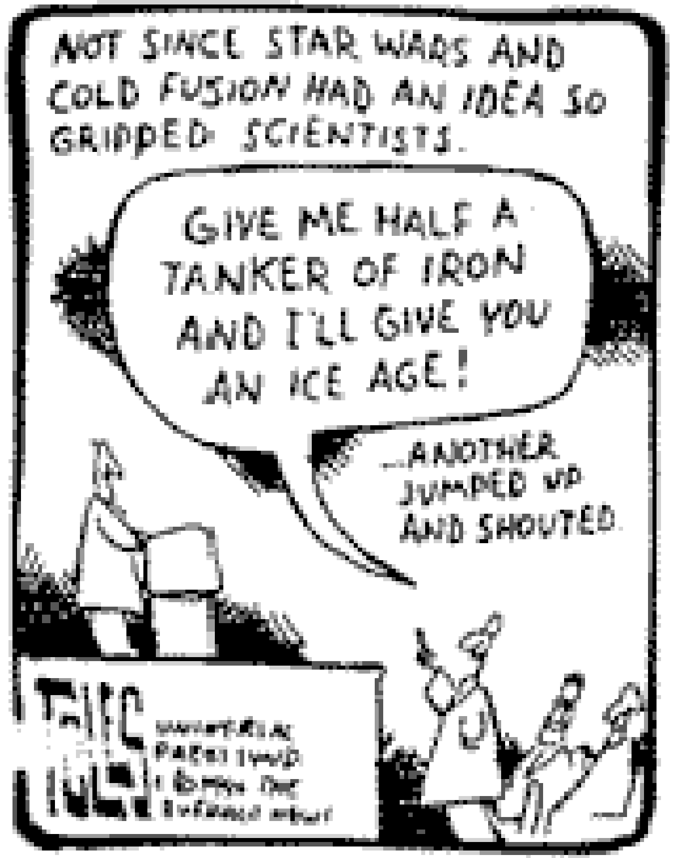
Stimulate soft tissue pump by adding nutrients: ocean iron fertilization, pump nutrients from depth into the surface layer (pipes)

Reduce $CaCO_3$ pump: small potential

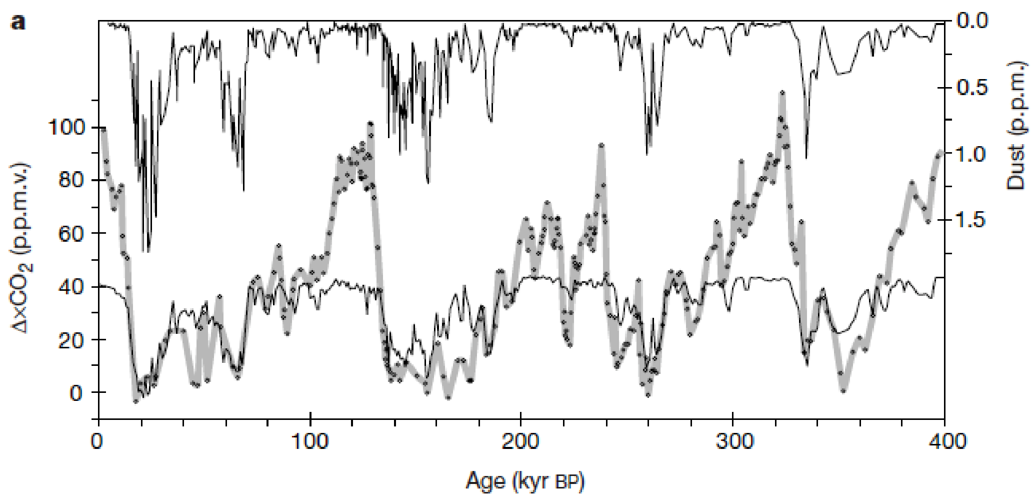
Increase physical/solubility pump: not feasible

Increase total alkalinity: artificially enhanced weathering

CO_2 sequestration in the ocean:
II Ocean Iron Fertilization (OIF)



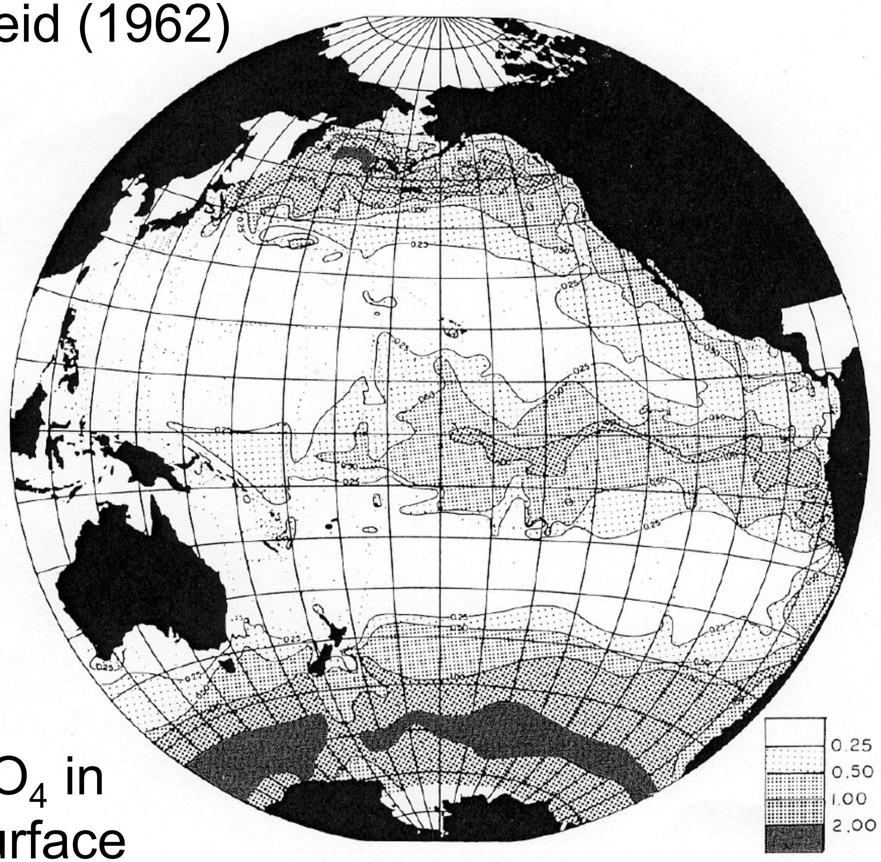
John Martin



Petit et al., 1999
Watson et al. 2000

High Nutrient (NO_3, PO_4) Low Chlorophyll (HNLC) regions

Reid (1962)



PO_4 in surface ocean

μmol L^{-1}

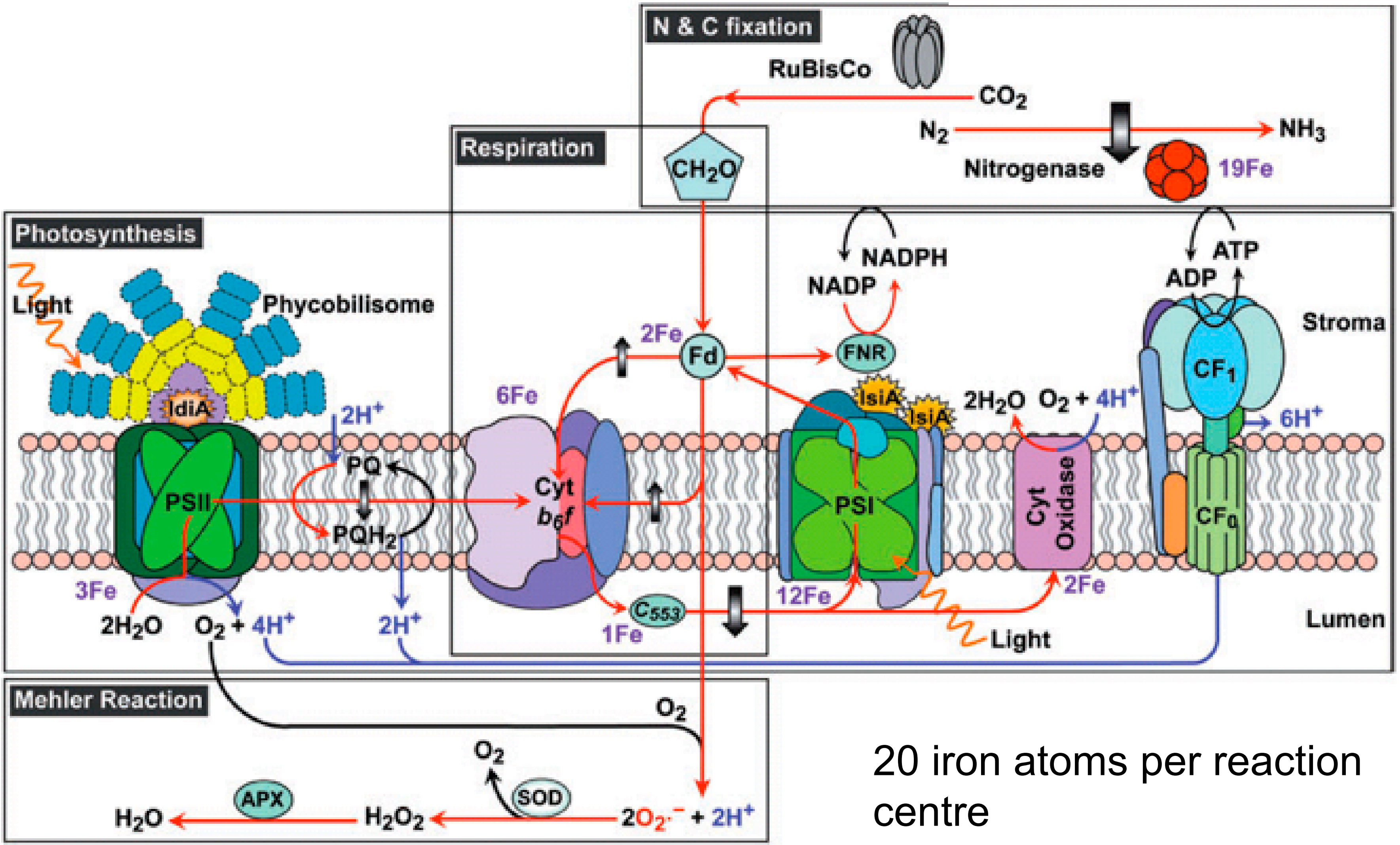
Northern North Pacific

Equatorial Pacific

Southern Ocean

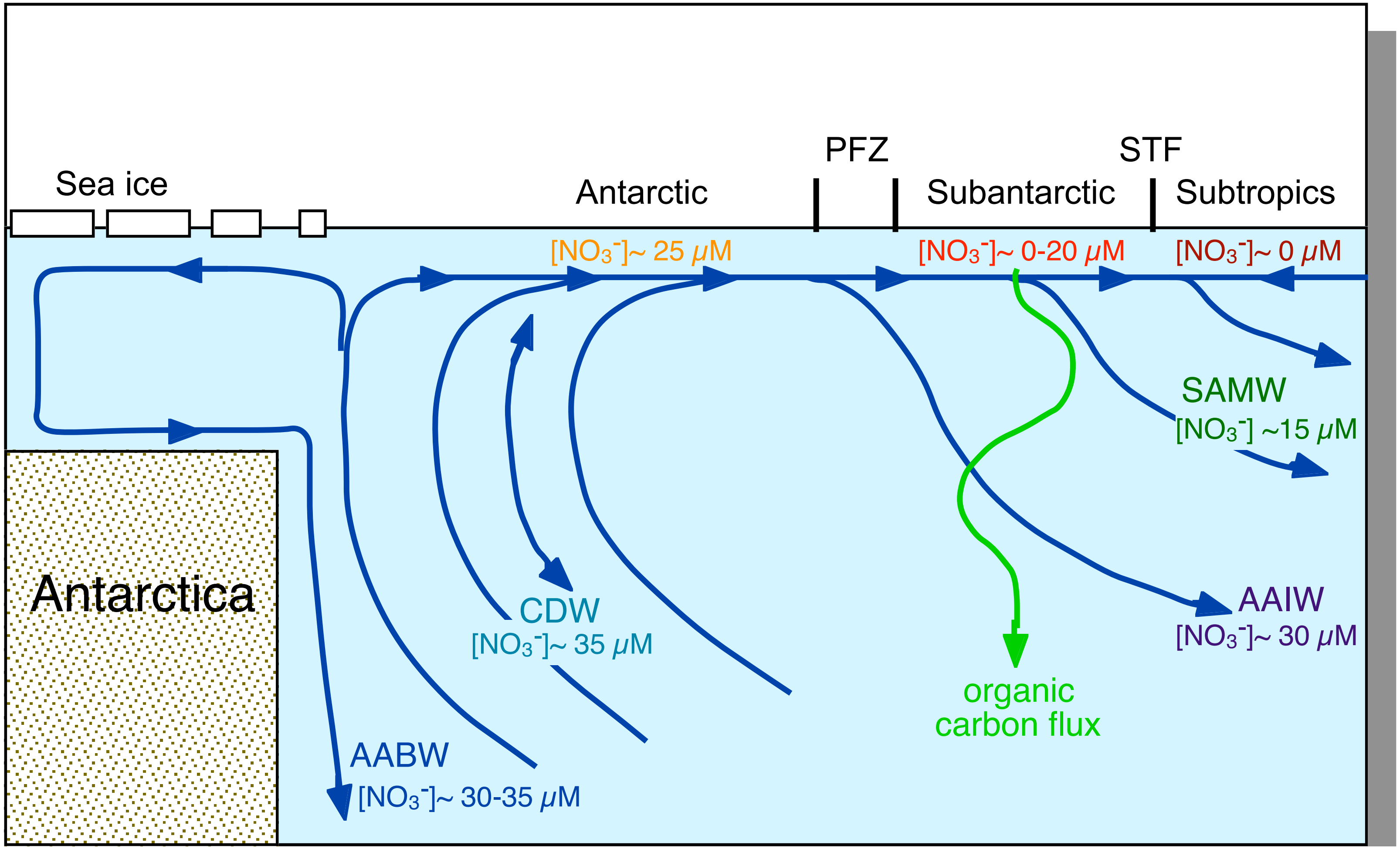
Iron in enzymes photosystem I & II

Shi et al., 2007



20 iron atoms per reaction centre

Potential for Fe fertilization in the Southern Ocean? Circulation & NO_3



PFZ = Polar Frontal Zone STF = Subtropical Front

AABW = Antarctic Bottom Water CDW = Circumpolar Deep Water

AAIW Antarctic Intermediate Water SAMW = Subantarctic Mode Water

Potential for Fe fertilization in the Southern Ocean?

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Macronutrients (NO_3, PO_4) leave the Southern Ocean via Antarctic Intermediate Water (AAIW) and mode waters without taking C along. Add Fe south of the AAIW/mode water formation regions to stimulate biological production and export of carbon from the surface layer.

Potential = water transport ($m^3\ yr^{-1}$) x NO_3 concentration (mol m^{-3})
x conversion to C (mol C (mol N)$^{-1}$)
x conversion to mass (g C (mol C)$^{-1}$) = **1.3 Pg C yr^{-1}**

34 Sv = 34 x $10^6\ m^3\ s^{-1}$ (Rintoul & Sloyan, 2001)

NO_3 = 15 μmol L^{-1}

Sarmiento & Orr (1991): Complete macronutrient depletion due to iron fertilization of HNLC regions $\Rightarrow$ 98 - 181 Pg C over 100 years
$\Rightarrow$ 1 - 1.8 Pg C yr^{-1}

Aumont & Bopp (2006): 70 Pg C over 100 years $\Rightarrow$ 0.7 Pg C yr^{-1}

Iron fertilization experiments

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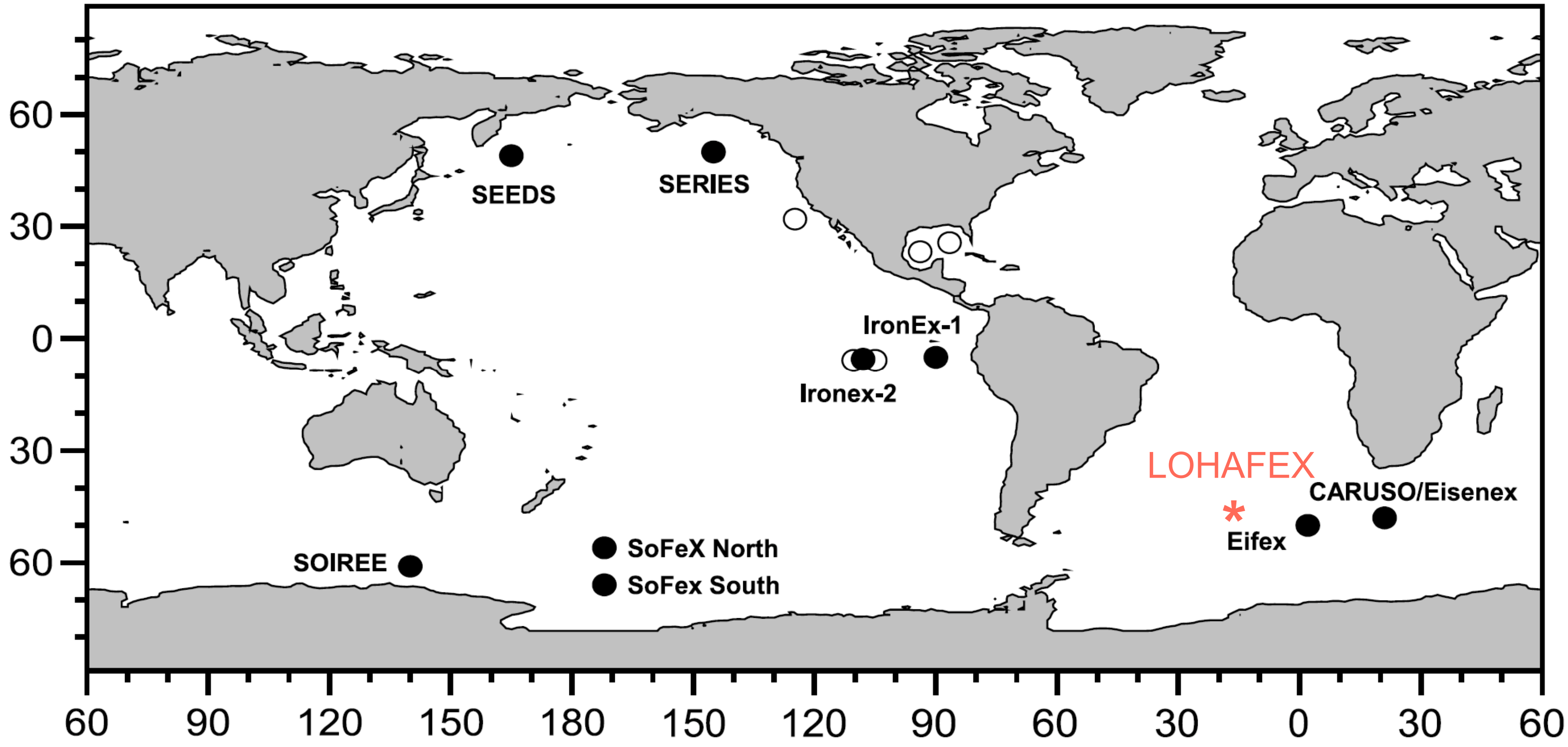


de Baar et al. 2005

LOHAFEX = LOHA (iron, Hindi) Fertilization EXperiment

7 January - 17 March 2009

Political storm

etc group
action group on erosion, technology and concentration

January 7, 2009

Sigmar Gabriel, MdB
z.H. Sören Heinze
Platz der Republik 1
11011 Berlin

GREENPEACE

HELMHOLTZ ASSOCIATION

-> write risk assessment
evaluated by British
Antarctic Survey,
IfM-GEOMAR Kiel
& reviews by
legal advisers

The Times

Close Window

Rogue ship sails into storm over experiment

Bobby Jordan **Published:Jan 11, 2009**

Critics say dumping fertiliser into ocean to 'fix' climate change is fraught with risk

South Africa is caught up in a diplomatic row over a rogue science ship that slipped out of Cape Town harbour to conduct a controversial climate change experiment.

The ship set sail on Wednesday night in breach of a UN ban on "fertilising" the ocean — and South Africa has been asked to intercept the vessel.

The German-flagged RV Polarstern is loaded with iron sulphate it plans to dump deep in the Southern Ocean during a 70-day research experiment conducted by German and Indian scientists.

The 20-ton chemical cargo — normally used to treat lawns and sewage — is likely to provoke a massive algal bloom big enough to be seen from outer space. Scientists are hoping the algae will provide a quick fix to climate change by absorbing carbon into the sea, rather than letting it escape as gas into the earth's atmosphere.

CONTROVERSIAL MISSION: The German-flagged RV Polarstern in Cape Town harbour this week. South Africa has been asked to intercept the ship. Picture: IAN SHIFFMAN


Chief - Victor Smetacek
AWI


Co Chief - Wajih Naqvi
NIO - Chemist

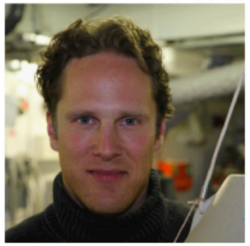

Michiel Rutgers van der Loeff
AWI - Geochemist


Hema Naik
NIO - Chemist


Maya Muthirenthy
NIO - Chemist


Reshma Kant
NIO - Student Chemistry


Dieter Wolf-Gladrow
AWI - Physicist


Phillip Assmy
AWI/GLOMAR - Biologist


Christine Klaas
AWI - Biologist


Sunita Mochemadkar
NIO - Student Biology


Divyashri Baraniya
NIO - Student Biochemistry


Gauri Mahadik
NIO - Student Biology


Jörg Wulf
MPI - Microbiologist


Bernhard Fuchs
MPI - Microbiologist


Friederike Ebersbach & Nike Fuchs
AWI - Students Biology


Gayatree Narvenkar
NIO - Chemist


Melana Soares
NIO - Chemist


Anand Methar
NIO - Electronics Technician


Patrick Martin
NOCS - Biochemist


Kevin Saw
NOCS - Engineer


Pieter Vandrommes
UPMC-CRNS - Biologist


Pradip Narvekar
NIO - Chemist


Hanamant Dalvi
NIO - Chemist


Rajdeep Roy
NIO - Student Biochemistry

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SZN - Biologist


Maurizio Ribera d'Alcala
SZN - Biologist


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Vineet Desai
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Humerto Gonzáles
UACh/COPAS - Biologist


Regino Martinez
CSIC/IMEDEA - Chemist


Luis Laglera
CSIC/IMEDEA - Chemist


Babasaheb Thorat
NIO - Student Chemistry


Shrikant Patil
NIO - Student Biology


Sujith Kalarikkal
NIO - Chemist


Anselmo Almeida
NIO - Physics technician


Marina Montresor
SZN - Biologist


Amit Sarkar
NIO - Student Chemist


Sanjay Singh
NIO - Student Microbiology


Anil Pratihary
NIO - Chemist


Mangesh Gauns
NIO - Biologist


Ramaiah Nagappa
NIO - Microbiologist


Sathya Gundlapally Reddy
CCMB - Microbiologist


Sundar Vetaikorumagan


Murti Vadalmani
NIO - Physicist


Ramabadran Rengarajan
PRL - Geochemist


Tom - Thomas Bresinsky
Director / Cinematographer

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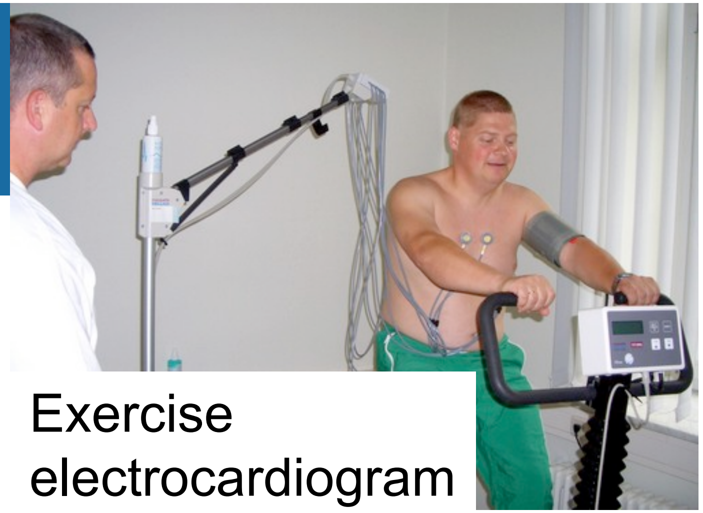
Perturbation experiment



Exercise electrocardiogram

... to investigate the structure and functioning of pelagic ecosystems

Pertubation:
Add 20 t of iron sulfate over an area of 300 km^2
≈ 4 t of iron ≈ 0.01 g Fe m^{-2}
(4000 m water column contains about ten times more Fe)

⇒ concentration in mixed layer: 2 nmol L^{-1}
(tap or mineral waters may show 100 times higher concentrations).

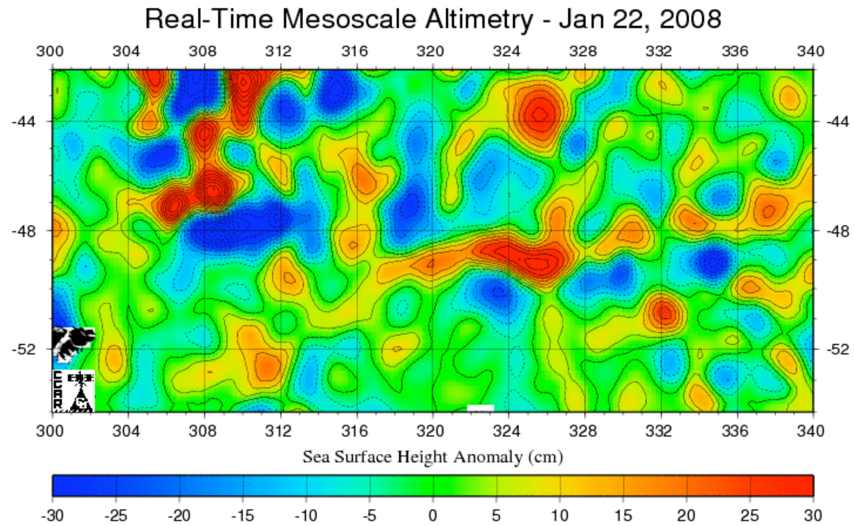
Avoid too much spreading/dilution of patch (initial radius 10 km) by fertilizing centre of a mesoscale eddy (radius 60 km)

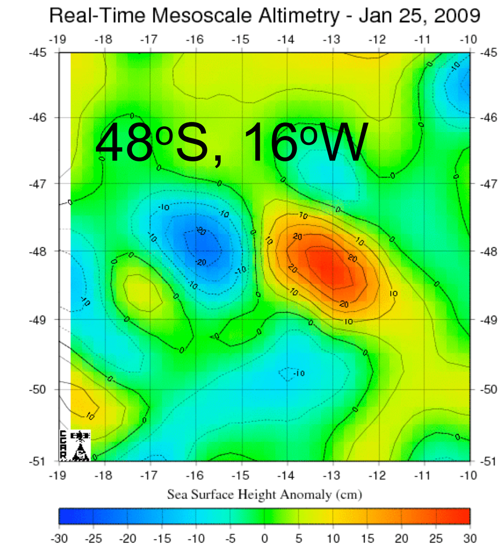
A good eddy should ...

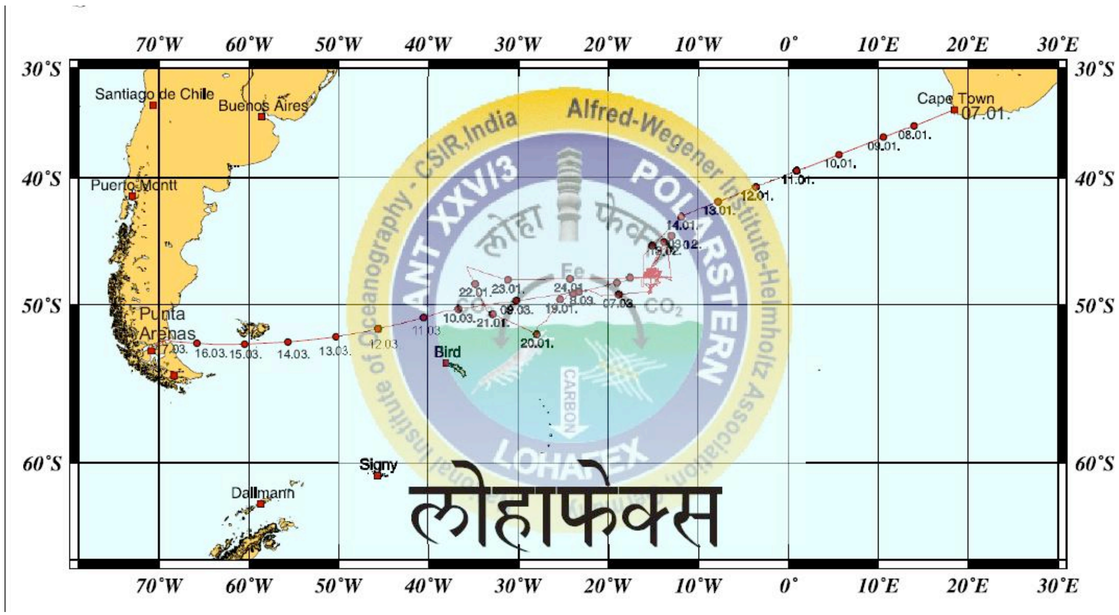
... be **stable** for at least 2 months.
(finite size Lyapounov exponents)

... contain **high nutrient concentrations** in surface layer.

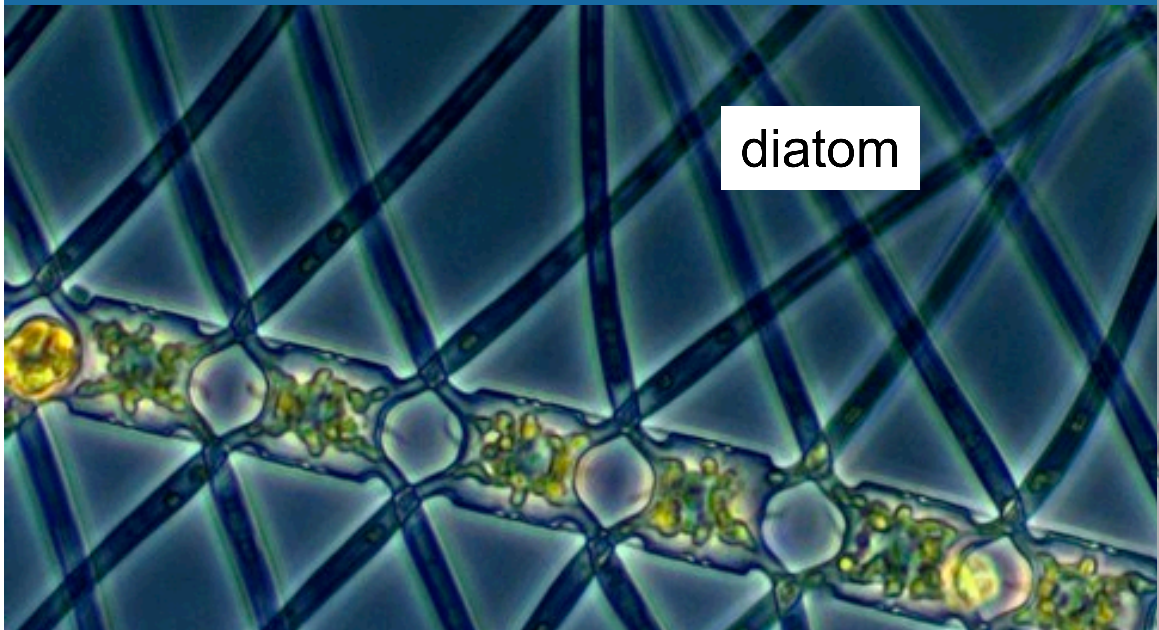
... contain a **seed population of phytoplankton**
(0.5 mg chlorophyll m^{-3} is lower limit).

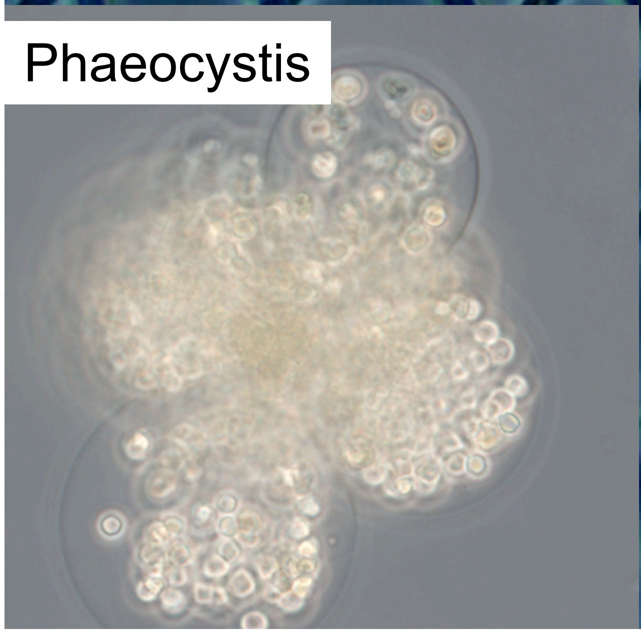


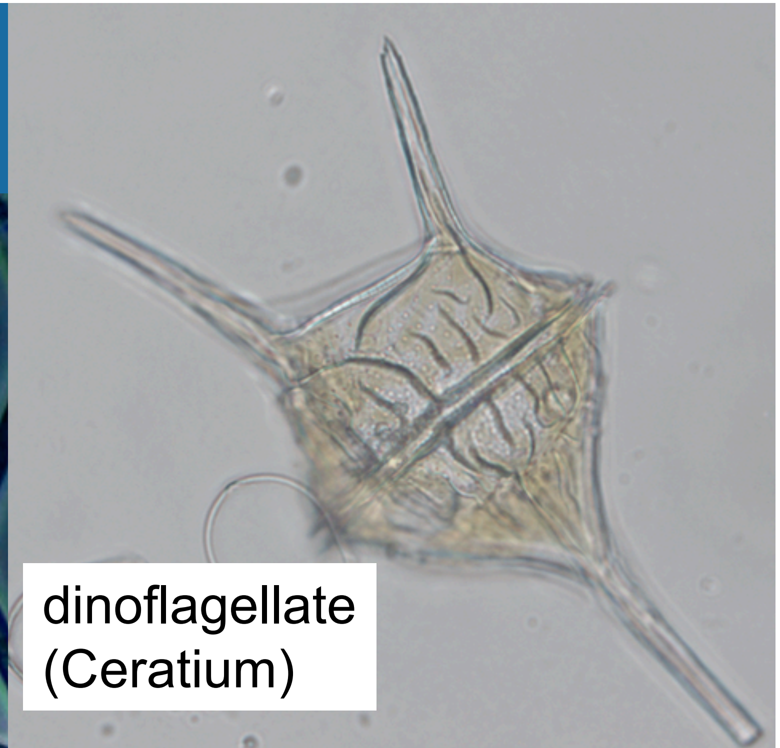


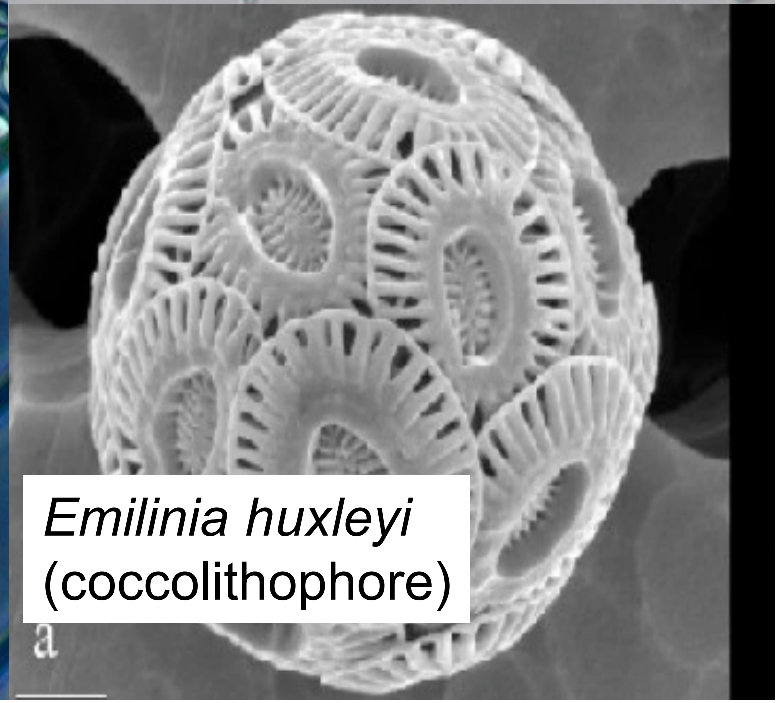


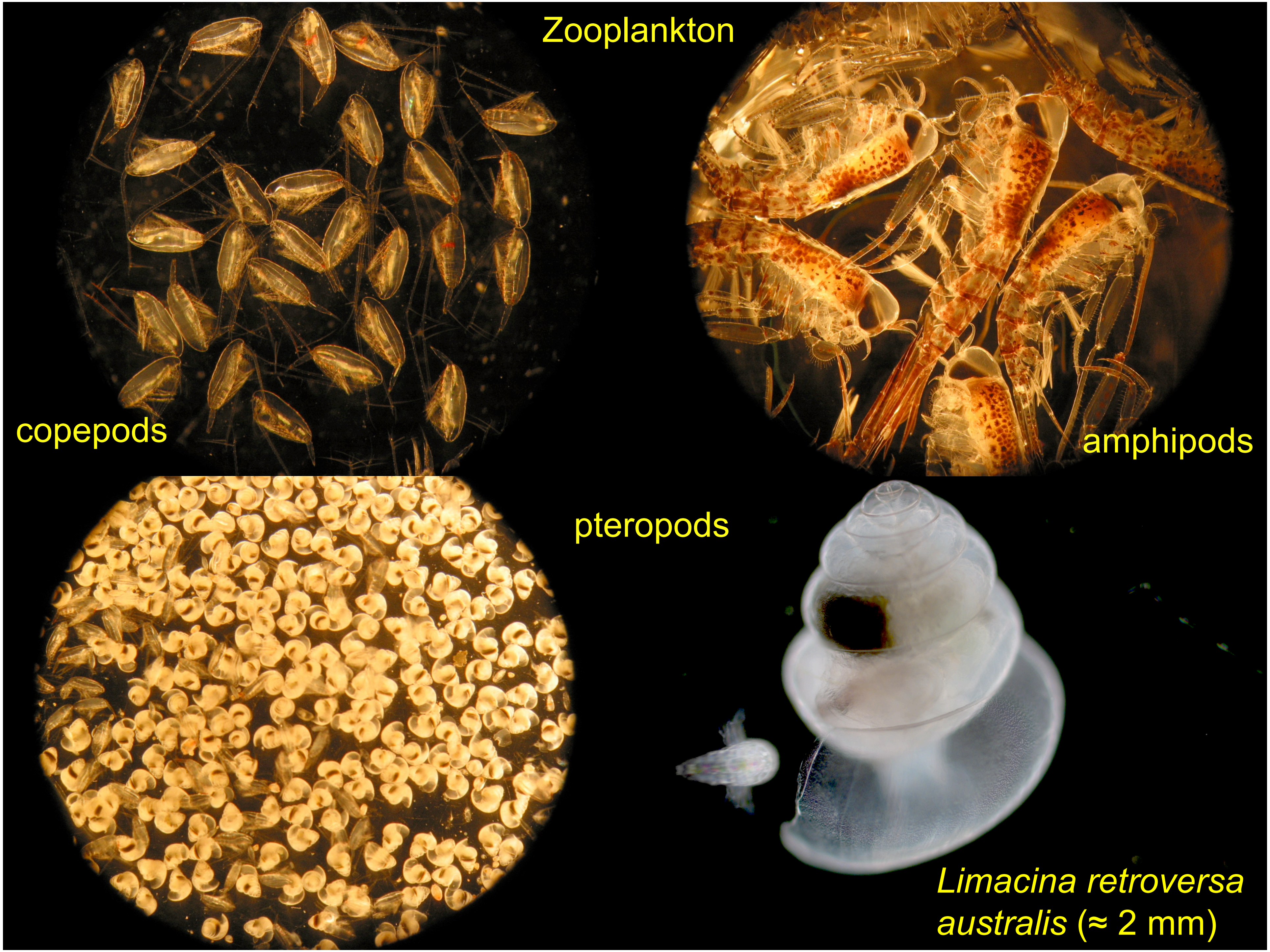
Phytoplankton:
Who will win?



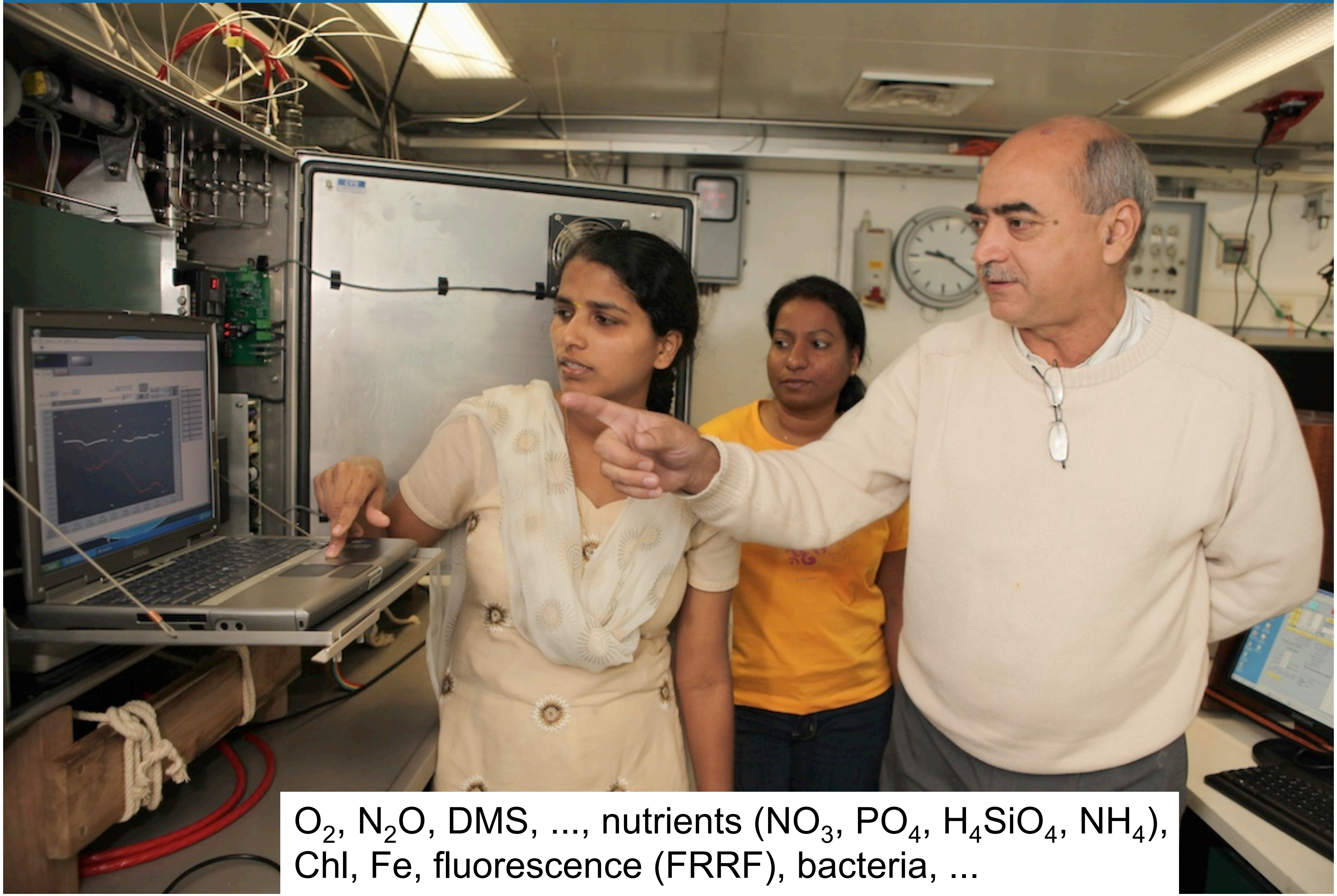







Zooplankton
copepods
amphipods
pteropods
Limacina retroversa australis (≈ 2 mm)

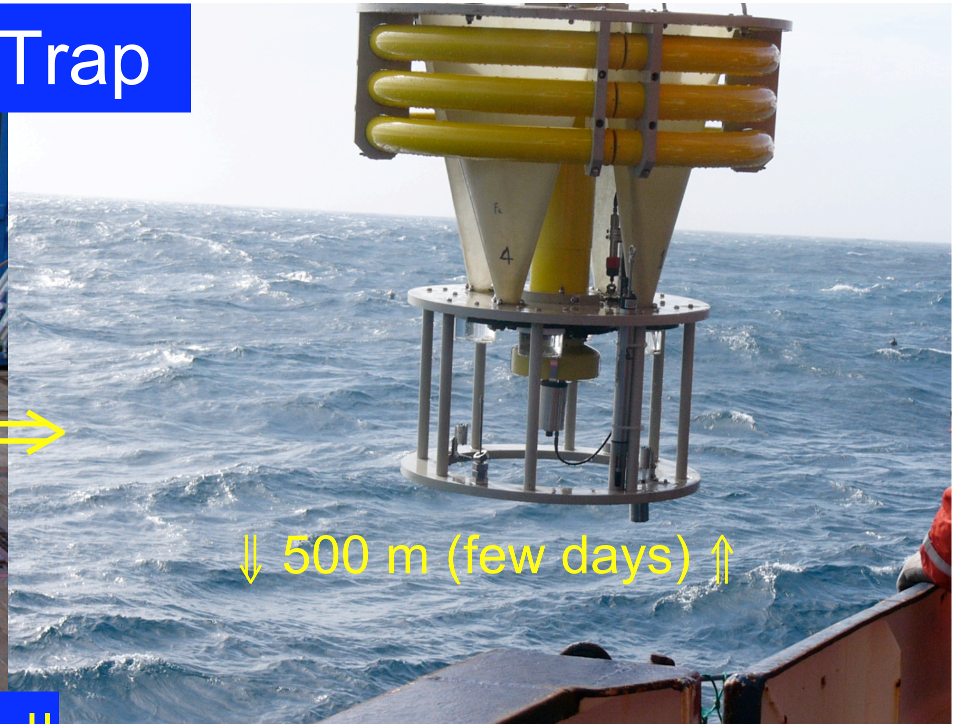
Measurements

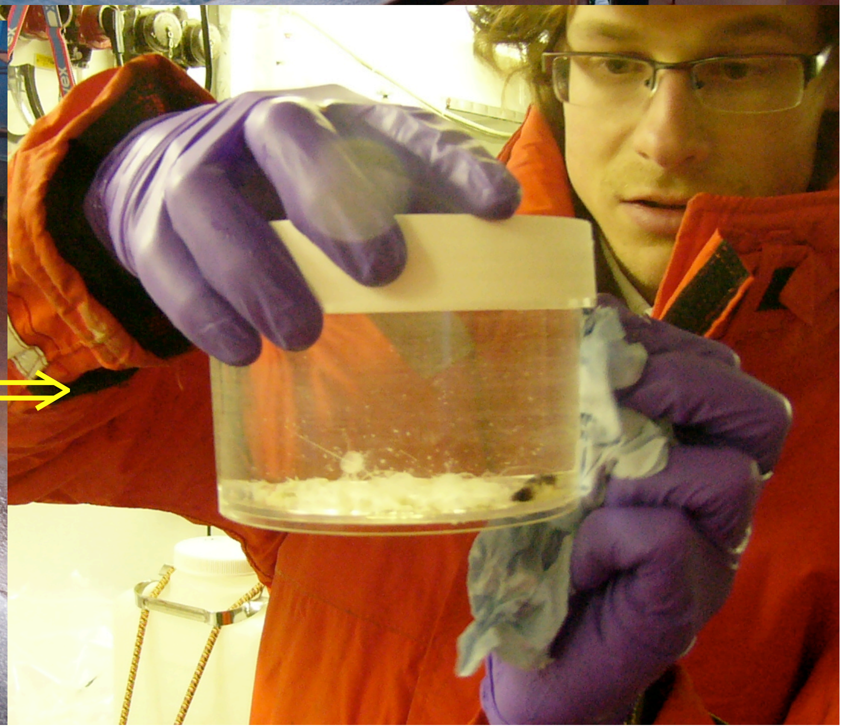


O_2, N_2O, DMS, ..., nutrients (NO_3, PO_4, H_4SiO_4, NH_4), Chl, Fe, fluorescence (FRRF), bacteria, ...

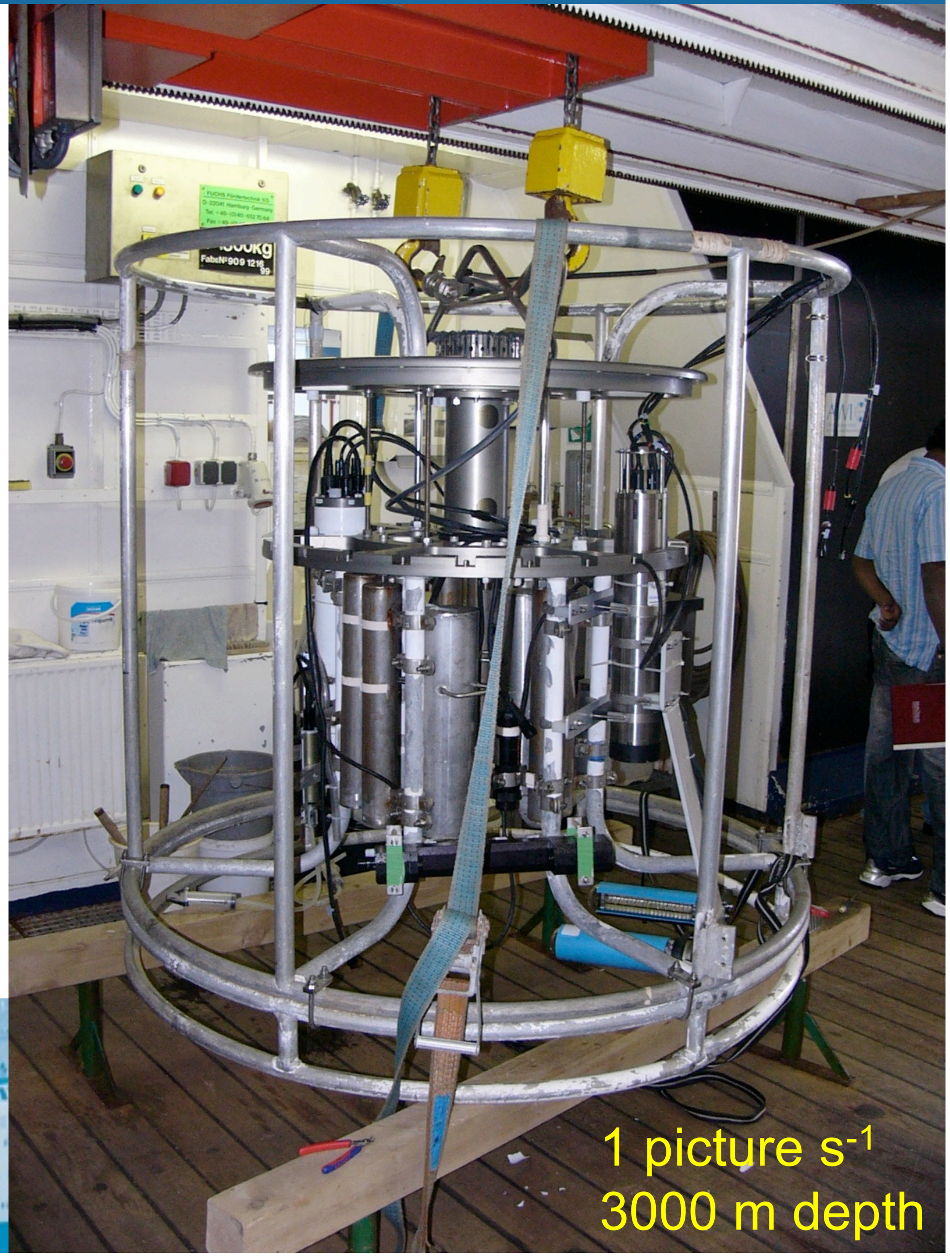
N_2O: no change

Neutrally Buoyant Sediment Trap

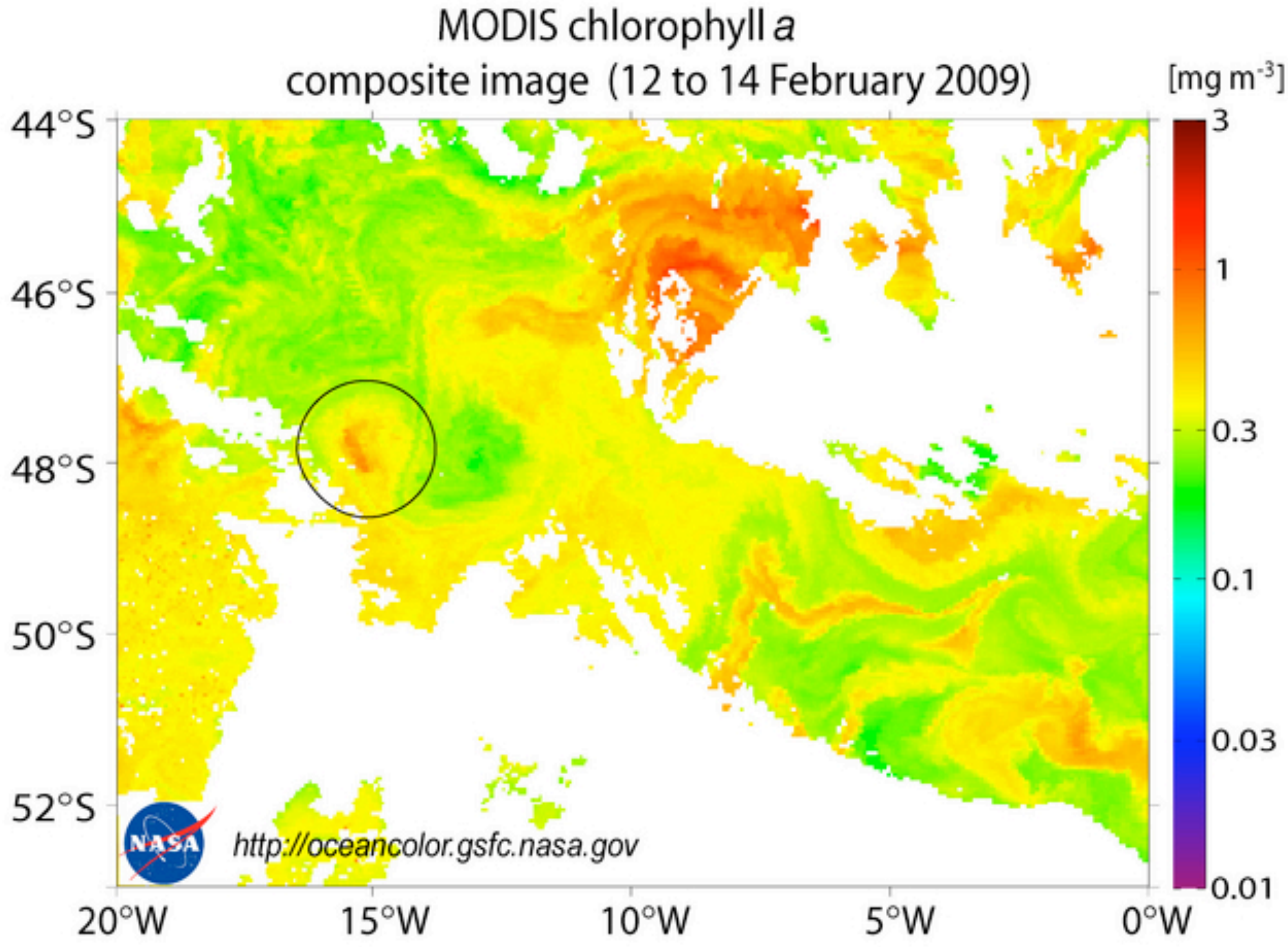




CTD rosette (Conductivity, Temperature, Depth)
Underwater Video Profiler (UVP)



LOHAFEX algal bloom



Carbon export? CO_2 uptake?

Chlorophyll increased by factor 2-3 (5 during EIFEX), mainly due to picophytoplankton.

Recycling system with considerable turnover.

⇒ Expectation: low carbon export.

Confirmed by sediment traps, particle recorder, ...

CO_2 uptake from atmosphere was low.

LOHAFEX: conclusions

Iron addition stimulated production. Accumulation rates of phytoplankton increased for a very short time only because of heavy grazing pressure by zooplankton. **Picophytoplankton and zooplankton profited most**. Positive effects are expected for higher trophic levels.

LOHAFEX showed that iron fertilization of nutrient-rich (NO_3,PO_4) waters does not necessarily lead to algal blooms, carbon export and thus CO_2 uptake (it‘s not just chemistry: $NO_3 + PO_4 + Fe \Rightarrow$ ...).

The state and functioning of the whole ecosystem plays an essential role; in particular: the plankton assemblage (initial conditions) and the amount of silicic acid.

⇒ Iron fertilization makes no sense here!

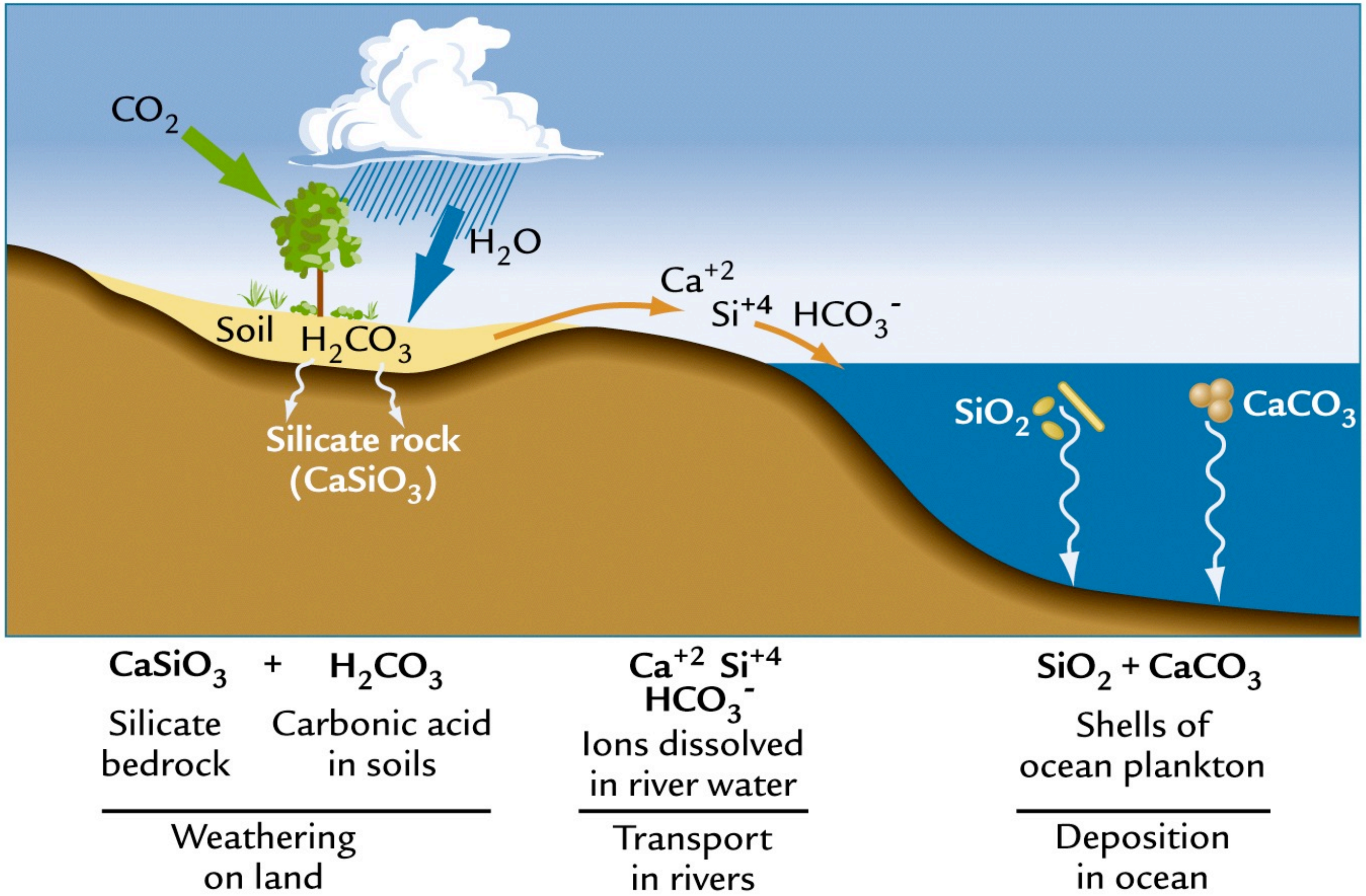
LOHAFEX: geoengineering or basic research?

Geoengineering: develop, optimize, and apply methods for the reduction of atmospheric greenhouse gases or reduction of incoming solar radiation in order to mitigate climate change. Observation of low C export is a failure.

Basic research: Investigate the structure and functioning of ecosystems under various conditions. Observation of low C export is a major result and not a failure.

When we came home from LOHAFEX we were exhausted & happy!

The C cycle on long time scales: weathering of silicate rock



(Ruddiman, 2000)

The net effect of weathering can be summarized into the basic equation
igneous rocks + acid volatiles ⇒ sedimentary rocks + salty ocean

Weathering rates depend on:

Surface to volume ratio of rock: mechanical weathering increases chemical weathering!

Temperature: reactions proceed faster in warmer climate

Precipitation: water is needed

Acidity of ground water: atmospheric CO_2 and organics have an influence

Artificially enhanced weathering of olivine

$Mg_2SiO_4 + 4\ CO_2 + 4\ H_2O \Rightarrow 2\ Mg^{2+} + 4\ HCO_3^- + H_4SiO_4$

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+ 2 Mg^{2+}: increase total alkalinity (TA)!

ENHANCED WEATHERING: AN EFFECTIVE AND CHEAP TOOL TO SEQUESTER CO_2

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Requirements: small grain size (< 10 μm), high temperature, low pH
-> reactors or soils in tropical regions

Abstract. Weathering and subsequent precipitation of Ca- and Mg-carbonates are the main processes that control the CO_2-concentration in the atmosphere. It seems logical, therefore, to use enhanced weathering as a tool to reduce rising CO_2-levels. This can be applied as a technology, by reacting captured CO_2 with olivine or calcium-silicates in autoclaves. It can also be applied extensively, by spreading fine-powdered olivine on farmland or forestland. Measures to control the CO_2-levels of the atmosphere will be adopted more readily if they also serve some broader economic goals. An effective strategy for CO_2 control will require many parallel approaches simultaneously.

Potential for olivine dissolution

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The geoengineering potential of artificially enhanced silicate weathering of olivine

Peter Köhler,[1] Jens Hartmann,[2] Dieter A. Wolf-Gladrow[1]

Consider olivine dissolution in catchment areas of Amazon & Congo.
1 g CO_2 sequestration ≈ 1 g olivine (-> huge amounts of olivine!)

Problems:

1. Increase of river pH from below 7 to 8 or 9 (‘river alkalinization’).
2. Dissolution of silicic acid would limit potential to < 1 Pg C yr^{-1}.

Ocean pipes: nutrients from the deep
Lovelock & Rapley (2007)

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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.

Measurements of the climate system show that the Earth is fast becoming a hotter planet than anything yet experienced by humans. Processes that would normally regulate climate are being driven to amplify warming. Such feedbacks, as well as the inertia of the Earth system — and that of our response — make it doubtful that any of the well-intentioned technical or social schemes for carbon dieting will restore the status quo. What is needed is a fundamental cure.

The oceans, which cover more than 70% of the Earth's surface, are a promising place to seek a regulating influence. One approach would be to use free-floating or tethered vertical pipes to increase the mixing of nutrient-rich waters below the thermocline with the relatively barren waters at the ocean surface. (We acknowledge advice from Armand Neukermans on engineering aspects of the pipes.) Water pumped up pipes — say, 100 to 200 metres long, 10 metres in diameter and with a one-way flap valve at the lower end for pumping by wave movement — would fertilize algae in the surface waters and encourage them to bloom. This would pump down carbon dioxide and produce dimethyl sulphide, the precursor of nuclei that form sunlight-reflecting clouds.

Such an approach may fail, perhaps on engineering or economic grounds. And the impact on ocean acidification will need to be taken into account.

But the stakes are so high that we put forward the general concept of using the Earth system's own energy for amelioration. The removal of 500 gigatonnes of carbon dioxide from the air by human endeavour is beyond our current technological capability. If we can't 'heal the planet' directly, we may be able to help the planet heal itself.

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AWI

Ocean pipes: nutrients & DIC from the deep
Dutreuil, Bopp, and Tagliabue (2009)

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``Unsurprisingly, we find that deploying an array of ocean pipes acts to increase atmospheric CO_2 by 1.4 ppm via a 5.1% reduction in cumulative FCO_2 [air to sea CO2 flux], despite augmenting carbon export by 5.6%. This is contrary to the expectations of Lovelock and Rapley (2007) and results from increased mixing with sub-surface DIC-rich waters (Table 1, as noted by Shepherd et al., 2007), which overwhelms any beneficial response due to increased export and alkalinity supply. The positive anomalies in biological productivity and carbon export are maximal over the first few years of the experiment and decay by 20–30% after 20 years of deployment (Fig. 4). We further note that if we eliminate the non-local effects and mix the entire global ocean then while carbon export is over 50% greater, atmospheric CO_2 increases by over 20 ppm. Accordingly, carbon export and FCO_2 are clearly decoupled in response to changes in ocean mixing.

Physical/solubility C pump: enhanced downwelling (Zhou & Flynn, 2005)

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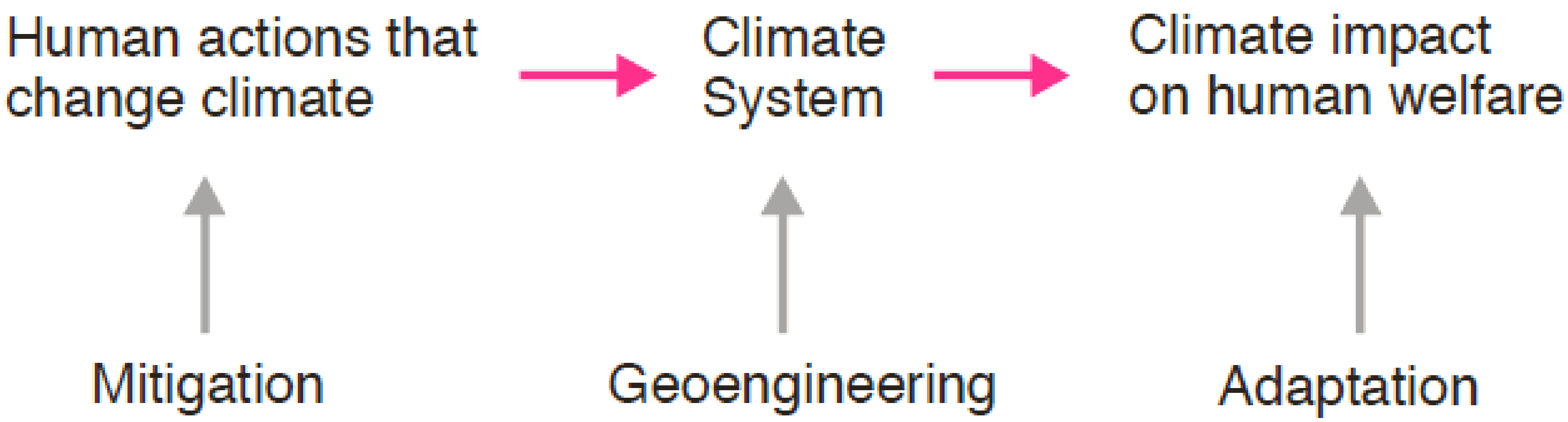
Abstract. Downwelling ocean currents carry carbon into the deep ocean (the solubility pump), and play a role in controlling the level of atmospheric carbon. The formation of North Atlantic Deep Water (NADW) also releases heat to the atmosphere, which is a contributor to a mild climate in Europe. One possible response to the increase in anthropogenic carbon in the atmosphere and to the possible weakening of the NADW is modification of downwelling ocean currents, by an increase in carbon concentration or volume. This study assesses the costs of seven possible methods of modifying downwelling currents, including using existing industrial techniques for exchange of heat between water and air. Increasing carbon concentration in downwelling currents is not practical due to the high degree of saturation of high latitude surface water. Two of the methods for increasing the volume of downwelling currents were found to be impractical, and four were too expensive to warrant further consideration. Formation of thicker sea ice by pumping ocean water onto the surface of ice sheets is the least expensive of the methods identified for enhancing downwelling ocean currents. Modifying downwelling ocean currents is highly unlikely to ever be a competitive method of sequestering carbon in the deep ocean, but may find future application for climate modification.

Final remarks: Mitigation/Geoengineering/Adaptation



Final remarks

Large scale experiment (Revelle & Suess, 1957): anthropogenic CO_2 emissions & climate change & ocean acidification

Finish this experiment (mitigation) or adapt to the consequences or counteract/combat the effects (geoengineering)

Some geoengineering methods (iron fertilization, enhanced silicate weathering) have the potential to sequester large amount of CO_2 in the ocean (order of 1 Pg C yr^{-1}).

These methods have (not well known) impacts on marine ecosystems (general problem for CO2 sequestration in the ocean).

Geoengineering: trade-off or torture?

Sustainable development


Thanks for your attention!

Title

Royal Society, London

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Geoengineering the climate

Science, governance and uncertainty

September 2009