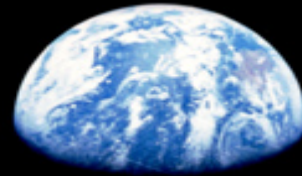
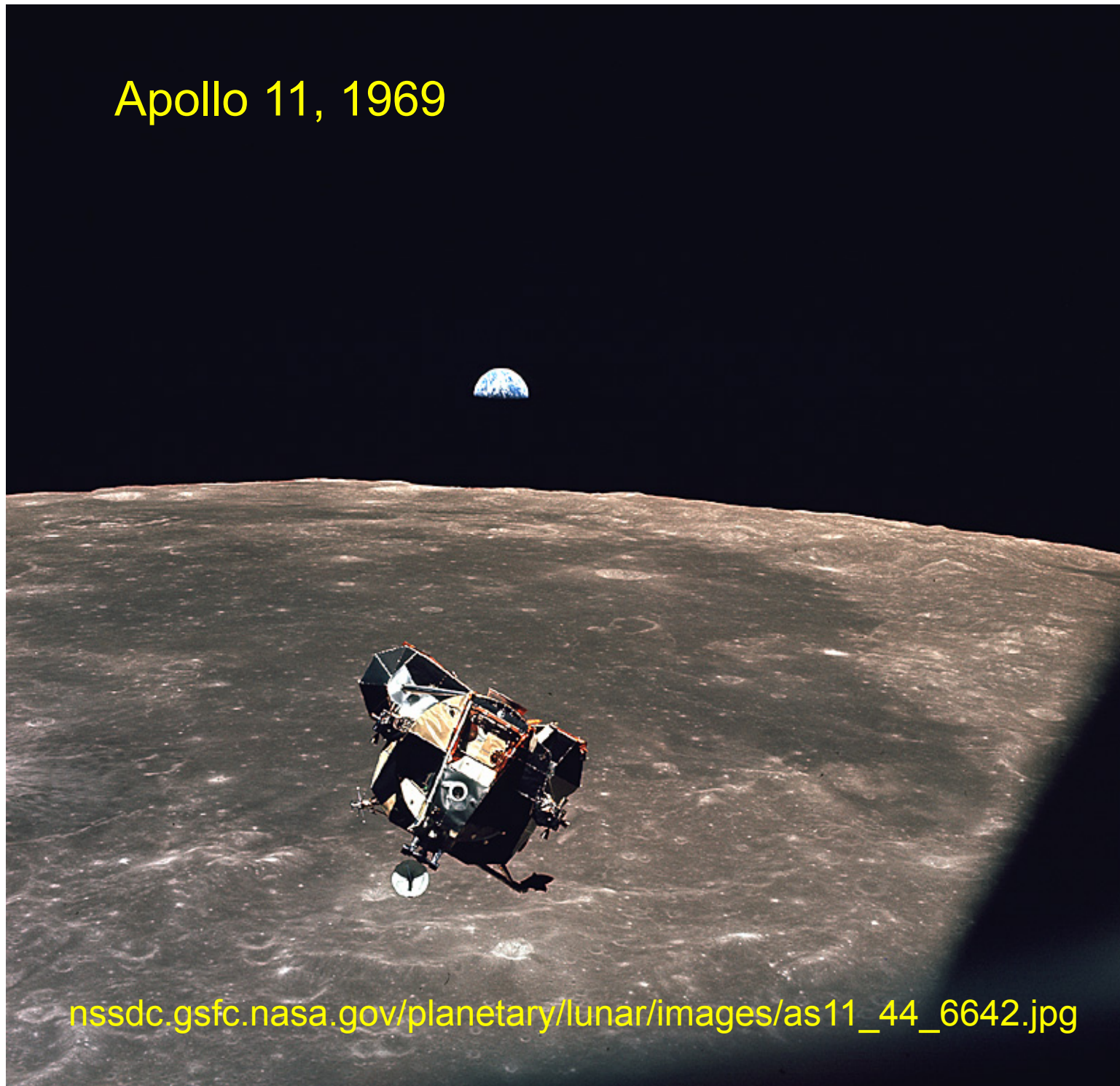


# Global Cycles of Biogenic Elements: Carbon



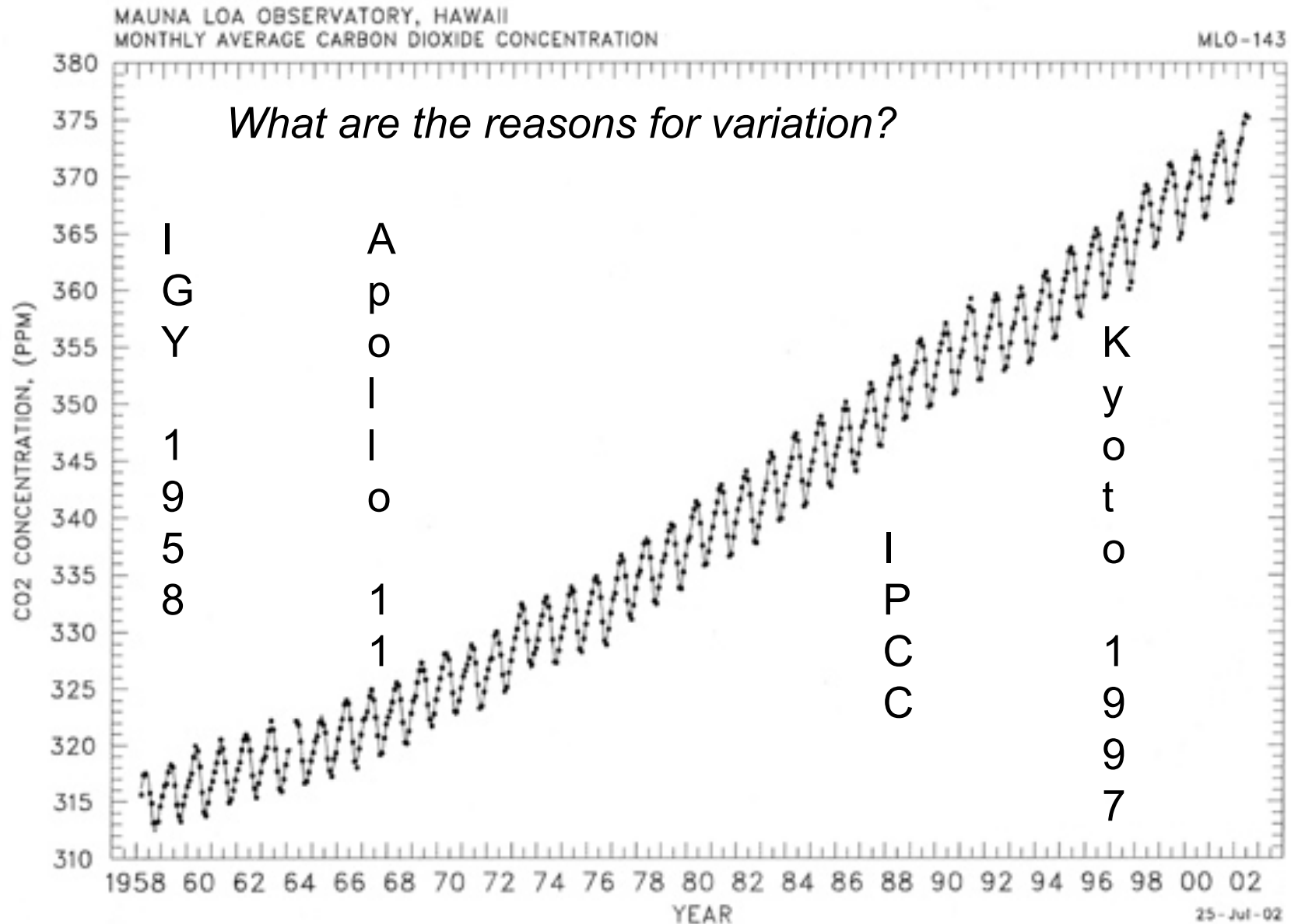
Dieter Wolf-Gladrow  
Alfred Wegener Institute  
for Polar and Marine Research  
[Dieter.Wolf-Gladrow@awi.de](mailto:Dieter.Wolf-Gladrow@awi.de)

# Apollo 11, 1969



[nssdc.gsfc.nasa.gov/planetary/lunar/images/as11\\_44\\_6642.jpg](https://nssdc.gsfc.nasa.gov/planetary/lunar/images/as11_44_6642.jpg)

# Mauna Loa CO<sub>2</sub> („Keeling“) curve





- 1958 International Geophysical Year (IGY)  
Charles David Keeling (1928-2005) started measurements of atmospheric CO<sub>2</sub> at Mauna Loa
- 1988 Intergovernmental Panel on Climate Change (IPCC)  
established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). 4. report 2007
- 1997 The **Kyoto Protocol** is a protocol to the international Framework Convention on Climate Change with the objective of reducing greenhouse gases in an effort to prevent anthropogenic climate change.  
Effective 2005-2012; 151 countries + European Union.  
Not ratified by USA.



# The Greenhouse Effect

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.

Solar radiation powers the climate system.



Some solar radiation is reflected by the Earth and the atmosphere.



ATMOSPHERE

EARTH

About half the solar radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

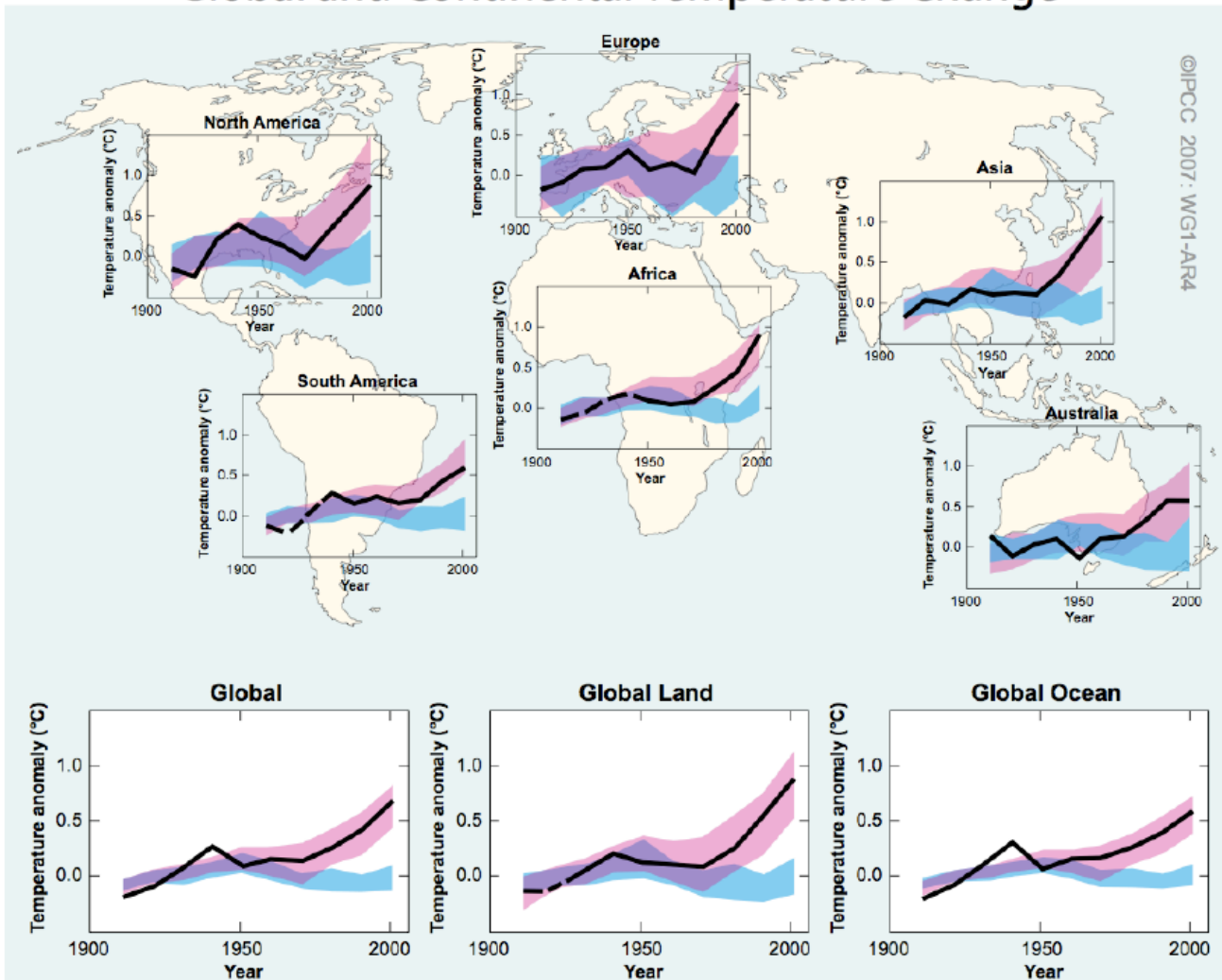


# Pierrehumbert (2011)

Infrared radiation and planetary temperature,  
Physics Today, 64(1), 33-38, 2011.

Excellent!

# Global and Continental Temperature Change



**FIGURE SPM-4.** Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 10%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. {FAQ 9.2, Figure 1}

IPCC, 2007



# Outline

Climate change is a major motivation to study cycles of elements.

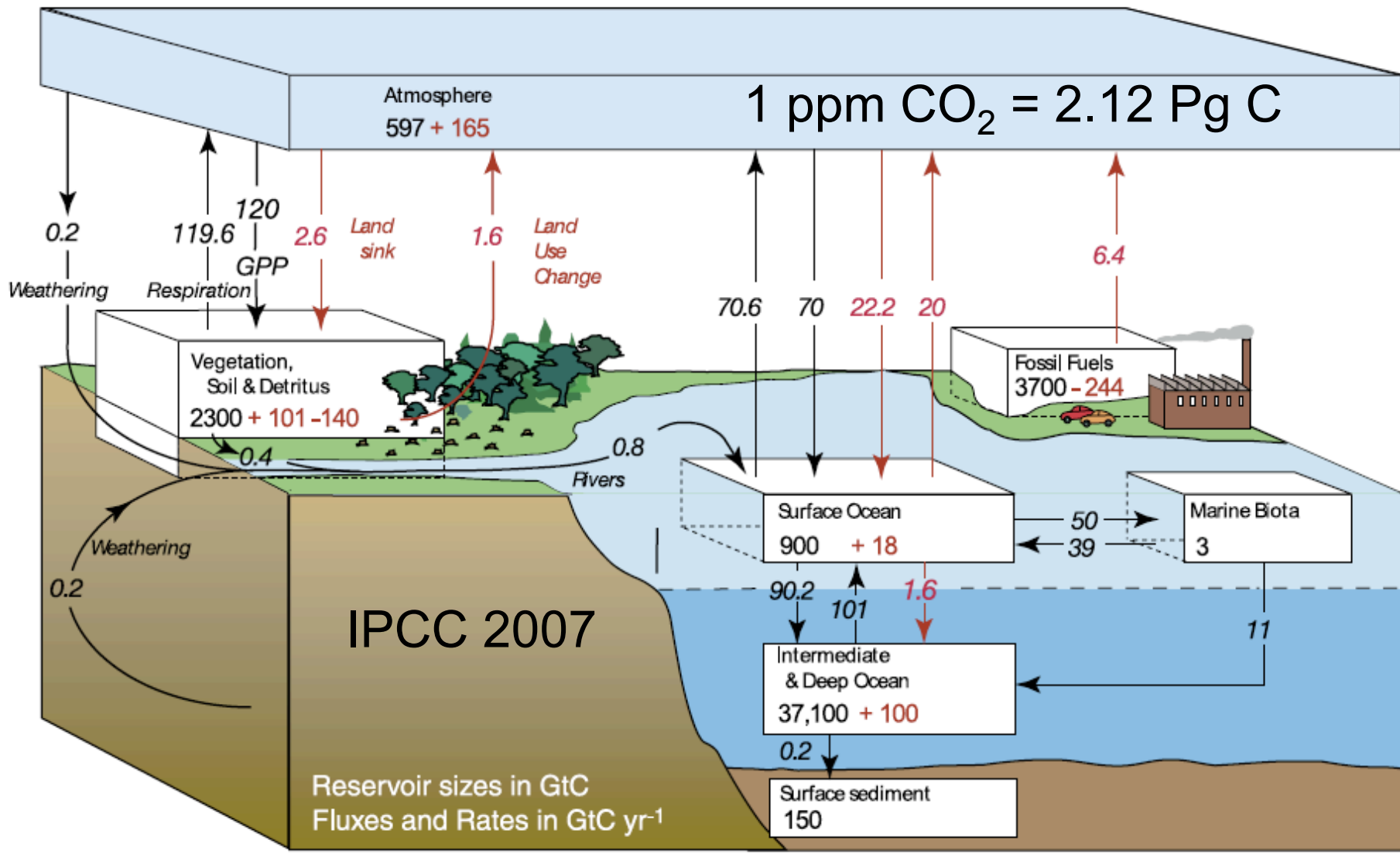
Natural variations, anthropogenic perturbations

**Carbon cycle: 4 active reservoirs, large natural fluxes, DIC + TA (conservative quantities), physical + biological carbon pumps, ...**

Coupling of elemental cycles by organisms:

C, N, P, O, S, Ca, Si, Fe, Zn, ...

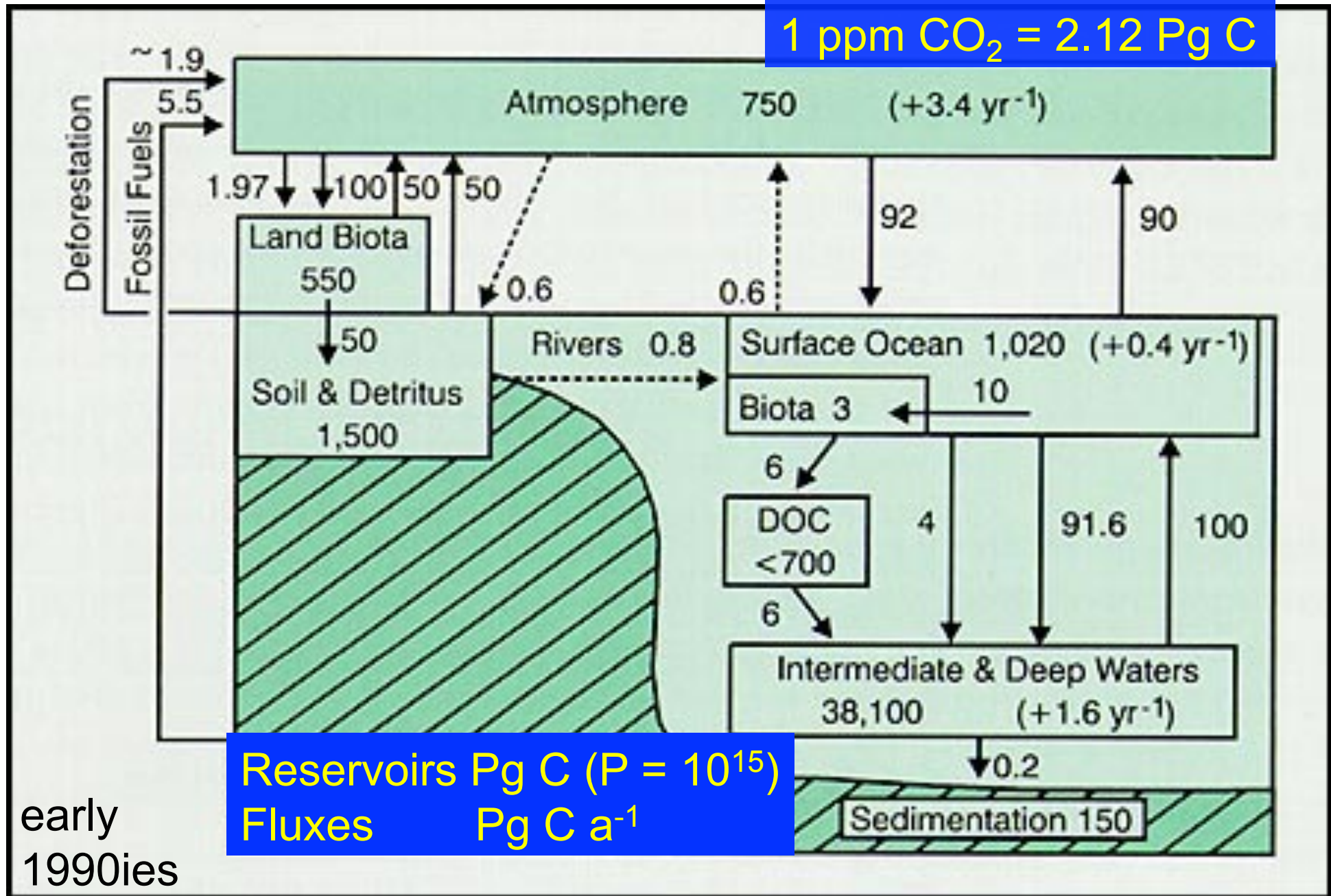
Climate-relevant gases: CO<sub>2</sub>, DMS, SO<sub>4</sub>, CH<sub>4</sub>, ...



1 Gt C = 1 Pg C = 10<sup>15</sup> g C

Some reservoir and flux sizes with large uncertainties.

# GLOBAL CARBON CYCLE <--> CLIMATE





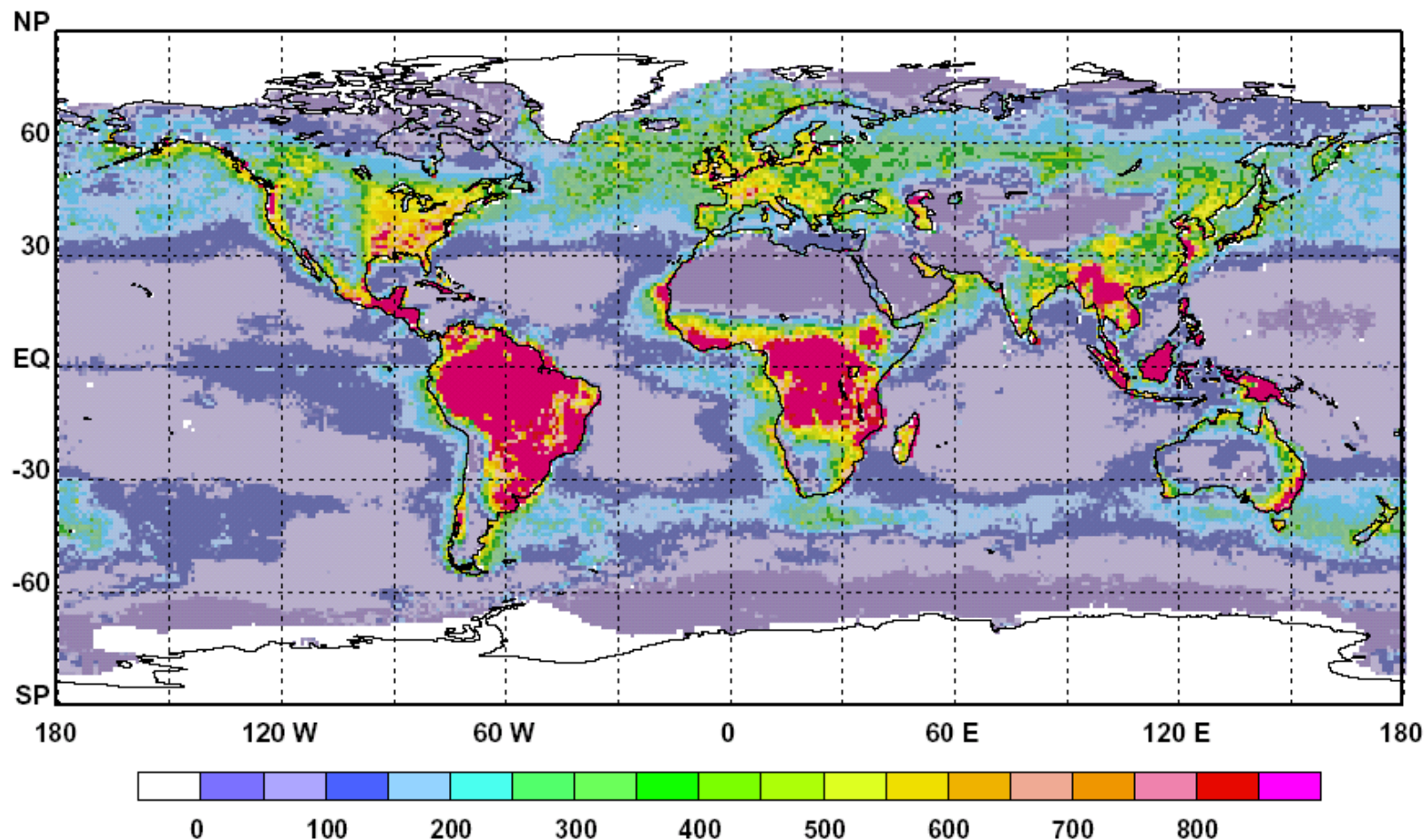
**Natural C fluxes are large:** 200 Pg C yr<sup>-1</sup> between atmosphere and land biota and ocean  
-> short mean residence time of atmospheric CO<sub>2</sub>: 3-4 yr

$\tau = \text{reservoir size (Pg C)} / \text{flux (Pg C yr}^{-1}\text{)}$

**Anthropogenic C fluxes much smaller than natural C fluxes, however, of different quality; input of C from inactive reservoirs.**

# Primary Production

**Fig. 1.** Global annual NPP (in grams of C per square meter per year) for the biosphere, calculated from the integrated CASA-VGPM model. The spatial resolution of the calculations is  $1^\circ \times 1^\circ$  for land and  $1/6^\circ \times 1/6^\circ$  for the oceans. Input data for ocean color from the CZCS sensor are averages from 1978 to 1983. The land vegetation index from the AVHRR sensors is the average from 1982 to 1990. Global NPP is  $104.9 \text{ Pg of C year}^{-1}$  ( $104.9 \times 10^{15} \text{ g of C year}^{-1}$ ), with 46.2% contributed by the oceans and 53.8% contributed by the land. Seasonal versions of this map are available at [www.sciencemag.org/feature/data/982246.shl](http://www.sciencemag.org/feature/data/982246.shl). NP, North Pole; EQ, equator; Sp, South Pole.



Field et al., 1998



# Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components

Christopher B. Field,\* Michael J. Behrenfeld, James T. Randerson,  
Paul Falkowski

Integrating conceptually similar models of the growth of marine and terrestrial primary producers yielded an estimated global net primary production (NPP) of 104.9 petagrams of carbon per year, with roughly equal contributions from land and oceans. Approaches based on satellite indices of absorbed solar radiation indicate marked heterogeneity in NPP for both land and oceans, reflecting the influence of physical and ecological processes. The spatial and temporal distributions of ocean NPP are consistent with primary limitation by light, nutrients, and temperature. On land, water limitation imposes additional constraints. On land and ocean, progressive changes in NPP can result in altered carbon storage, although contrasts in mechanisms of carbon storage and rates of organic matter turnover result in a range of relations between carbon storage and changes in NPP.

Science  
1998

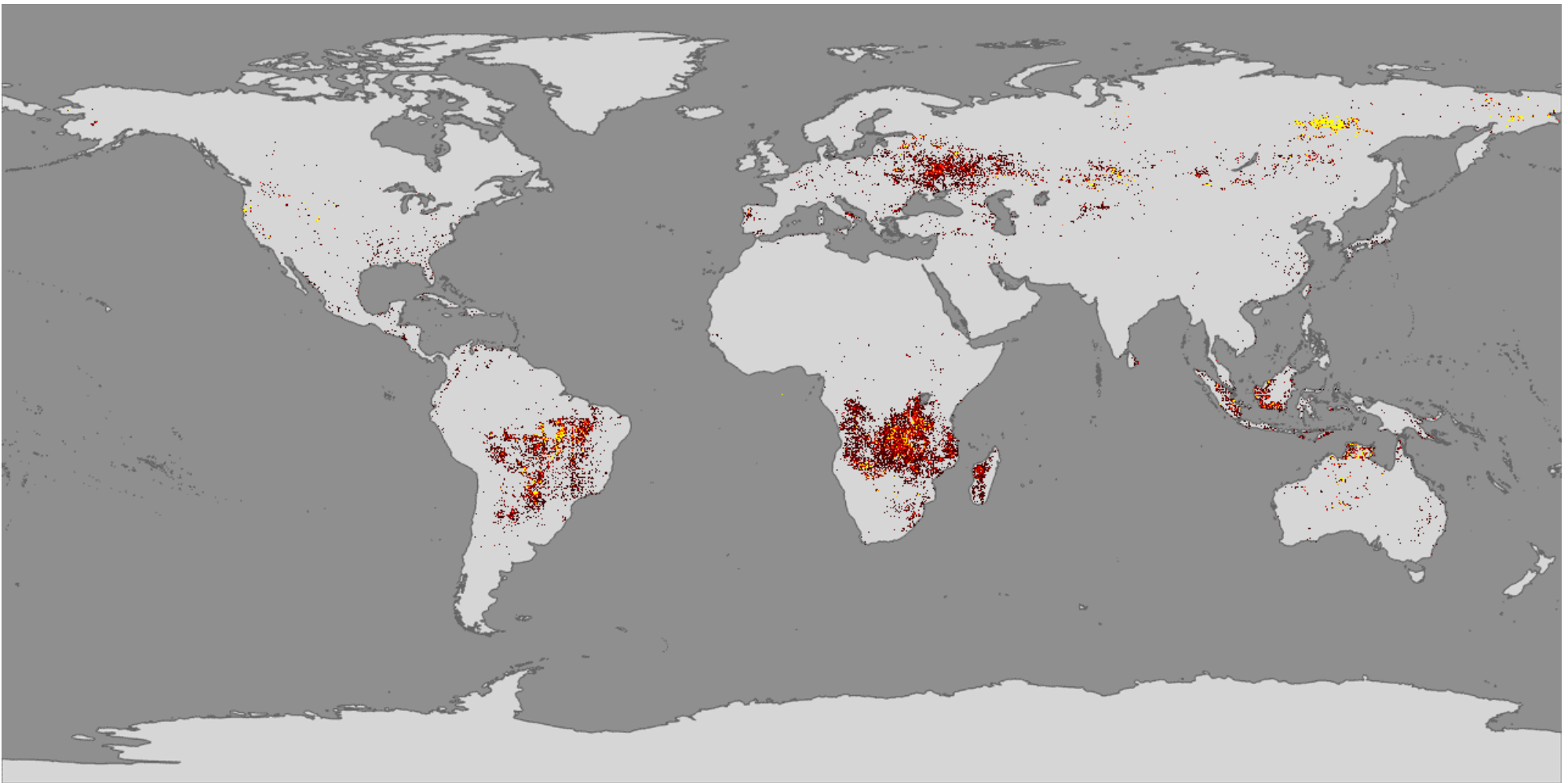
# Anthropogenic CO<sub>2</sub>: sources



Anthropogenic perturbations:  
CO<sub>2</sub> emissions





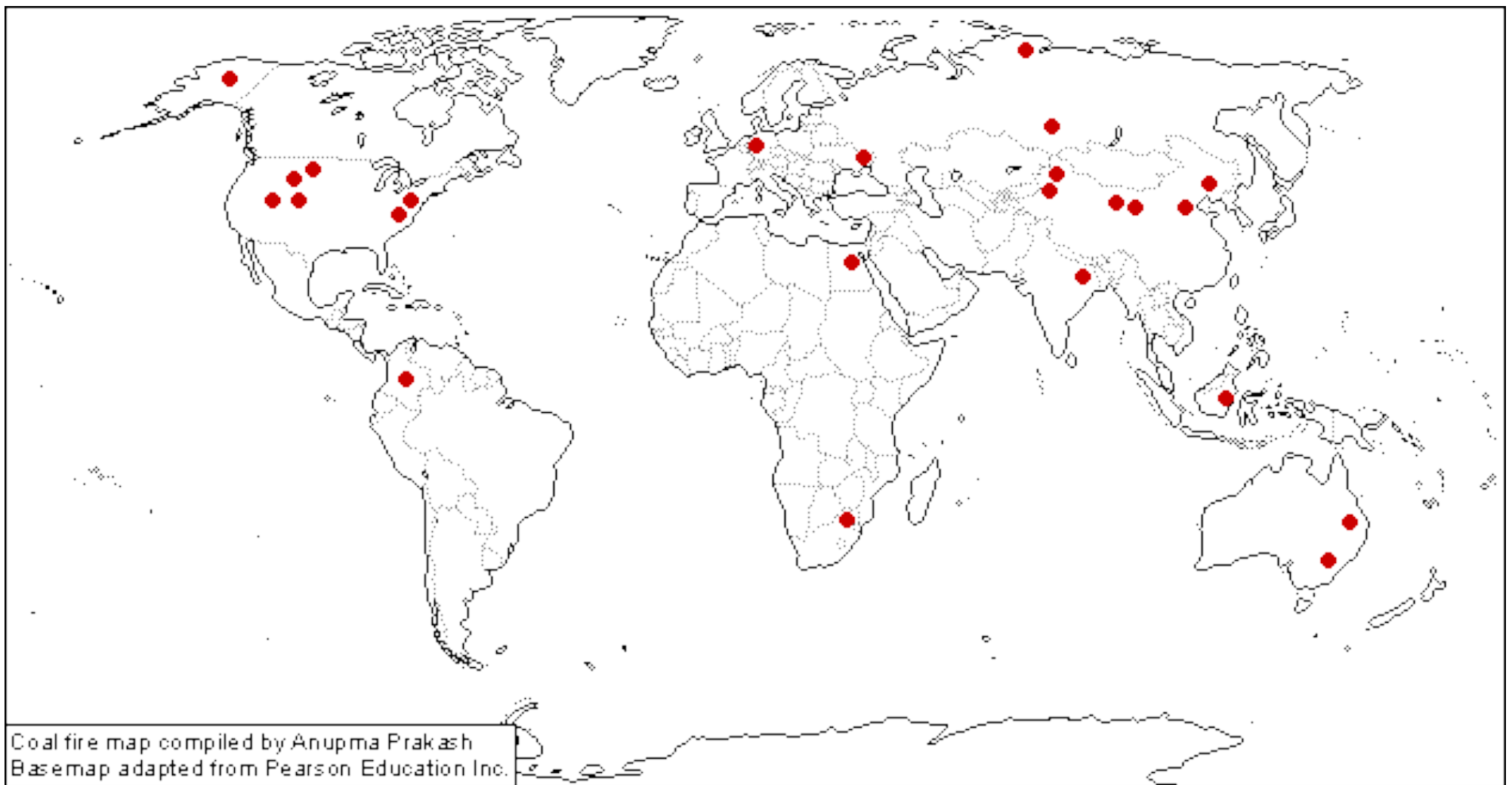


The image above shows fires during August 15–22, 2002. The greatest concentrations of fires are in the Amazon, Southern Africa, and Eastern Europe. In addition, there is a dense concentration of fires in Siberia. (Modis)



Photo: Anupma Prakash © 2000

This is a photograph of a coal fire in an open pit mining area in the Rujigou coalfield in China. The coal fire area is being actively mined. Here the coal seam is collapsing due to consumption of coal by the coal fire.



[http://www.gi.alaska.edu/~prakash/coalfires/global\\_distribution.html](http://www.gi.alaska.edu/~prakash/coalfires/global_distribution.html)

Year 2000: coal fires in China = coal production in Germany

## Carbon dioxide emissions rise to record levels

Carbon dioxide emissions from fossil fuels and cement manufacturing are rising faster than the worst-case scenario drawn up by the Intergovernmental Panel on Climate Change (IPCC). According to the latest worldwide carbon budget, released by the Global Carbon Project, CO<sub>2</sub> levels rose by 3.5% a year between 2000 and 2007, compared with 2.7% as calculated by the IPCC. During the 1990s, emissions rose at 0.9% a year.

“For a decade we’ve been using the [IPCC] middle-ground scenario, while we’re actually in a different realm of emissions,” says Pep Canadell, the project’s executive director.

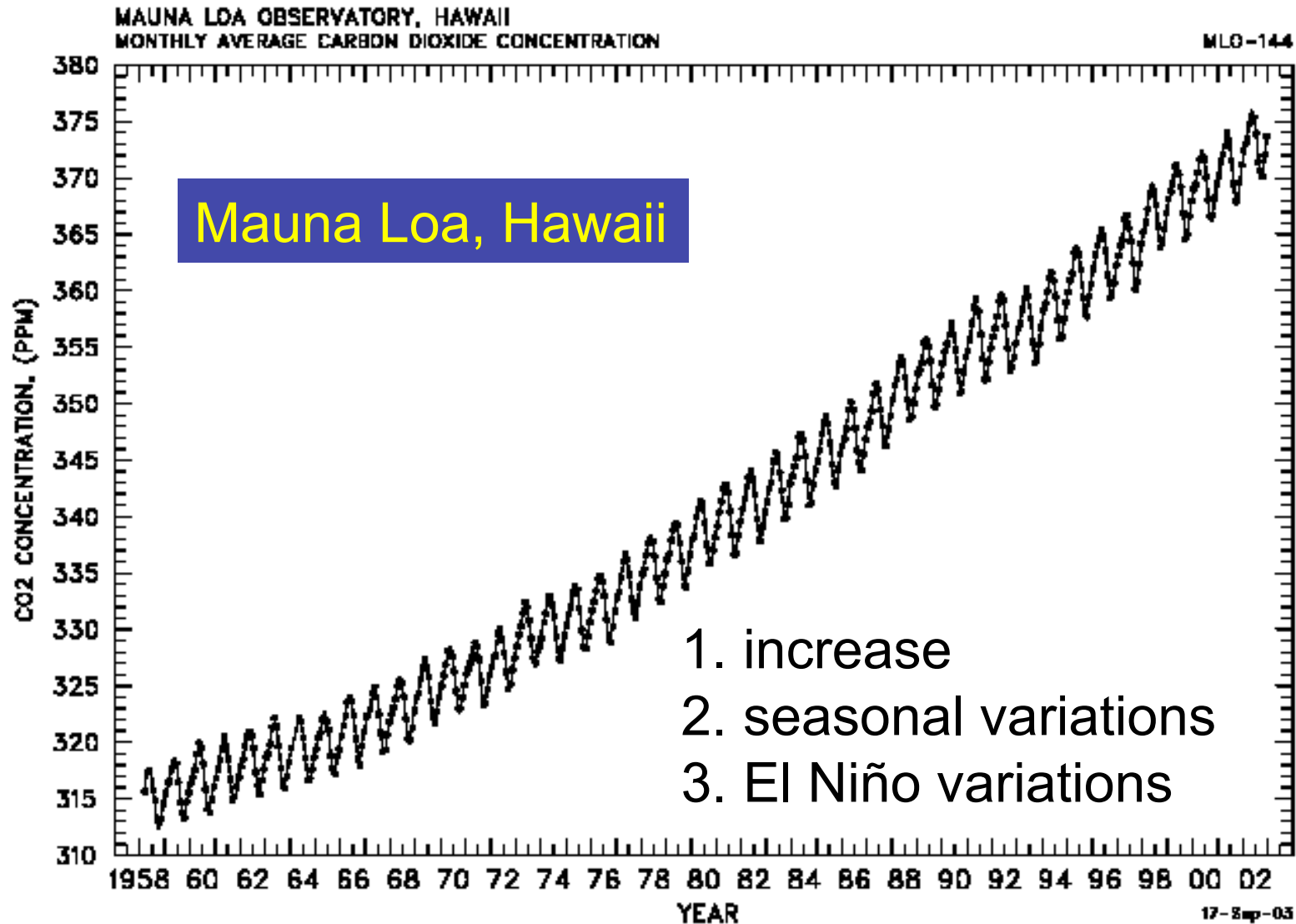
China is now the biggest emitter of CO<sub>2</sub> and responsible for 21% of the world’s emissions — up from 14% in 2002. This knocks the United States into second place, contributing 19% of global emissions. India is fourth, but looks set to take third place from Russia this year.

However, per capita  
CO<sub>2</sub> emissions:  
USA >> China

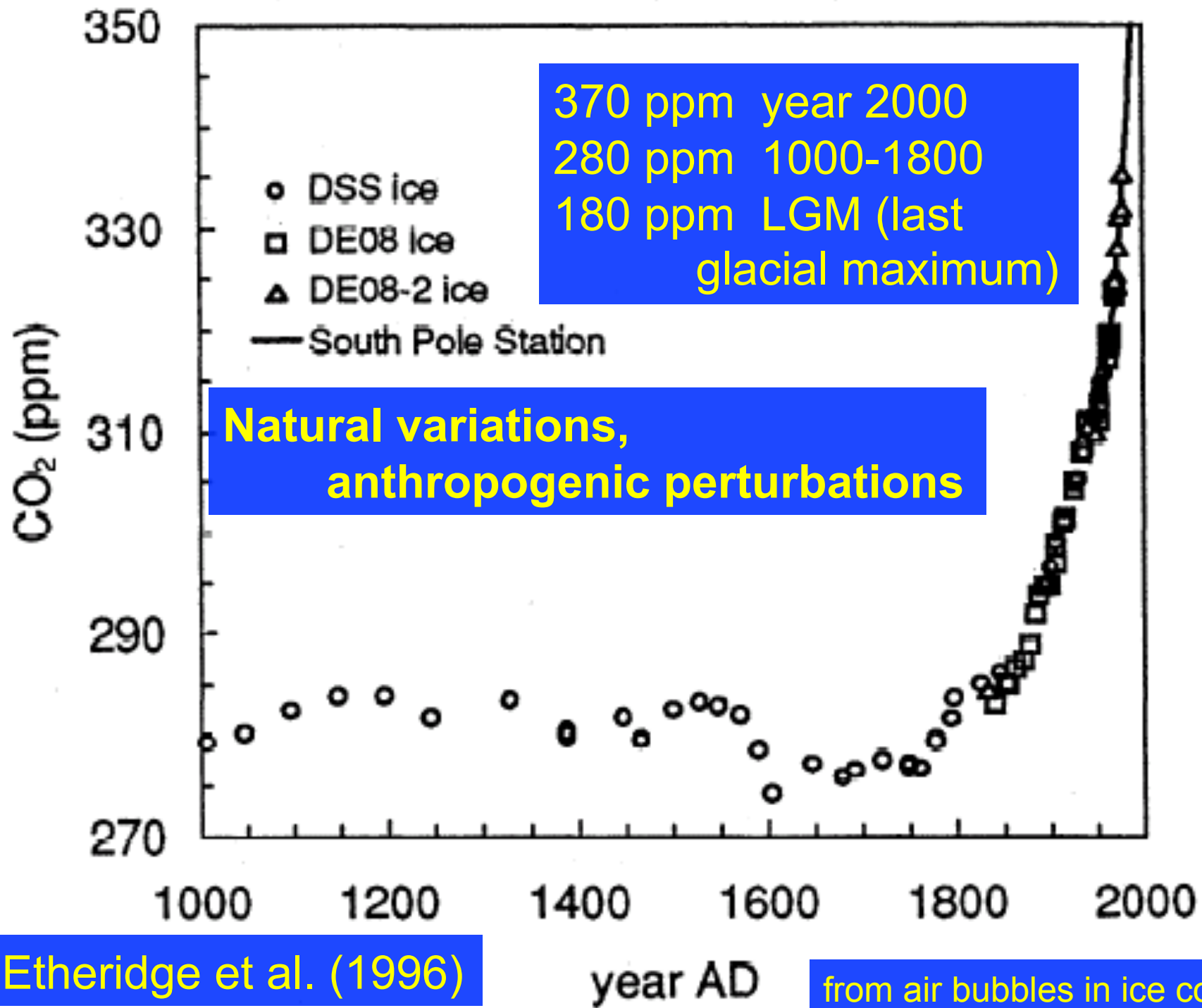
NATURE|Vol 455|2 October 2008  
p.581



# CO<sub>2</sub> in the atmosphere

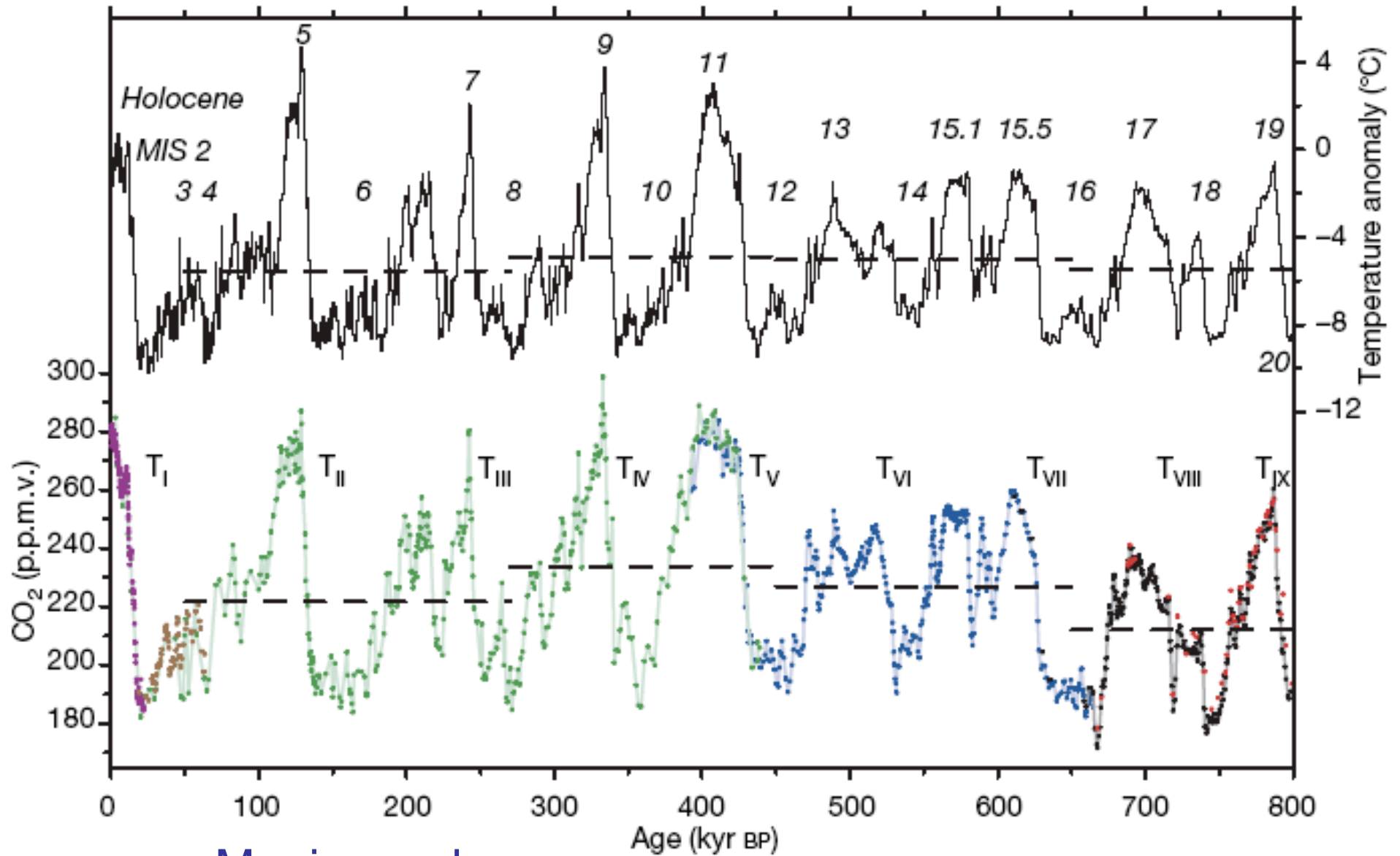






Etheridge et al. (1996)

from air bubbles in ice cores



Magic numbers:

172 ppm

300 ppm

Lüthi et al., 2008

Nature

**Figure 2 | Compilation of CO<sub>2</sub> records and EPICA Dome C temperature anomaly over the past 800 kyr.** The Dome C temperature anomaly record with respect to the mean temperature of the last millennium<sup>8</sup> (based on original deuterium data interpolated to a 500-yr resolution), plotted on the EDC3 timescale<sup>13</sup>, is given as a black step curve. Data for CO<sub>2</sub> are from Dome C (solid circles in purple<sup>5</sup>, blue<sup>4</sup>, black: this work, measured at Bern; red open circles: this work, measured at Grenoble), Taylor Dome<sup>6</sup> (brown) and Vostok<sup>1-3</sup> (green). All CO<sub>2</sub> values are on the EDC3\_gas\_age scale<sup>26</sup>. Horizontal lines are the mean values of temperature and CO<sub>2</sub> for the time periods 799–650, 650–450, 450–270 and 270–50 kyr BP. Glacial terminations are indicated using Roman numerals in subscript (for example T<sub>1</sub>); Marine Isotope Stages (MIS) are given in italic Arabic numerals<sup>27</sup>.

# High-resolution carbon dioxide concentration record 650,000–800,000 years before present

Dieter Lüthi<sup>1</sup>, Martine Le Floch<sup>2</sup>, Bernhard Bereiter<sup>1</sup>, Thomas Blunier<sup>1†</sup>, Jean-Marc Barnola<sup>2</sup>, Urs Siegenthaler<sup>1</sup>, Dominique Raynaud<sup>2</sup>, Jean Jouzel<sup>3</sup>, Hubertus Fischer<sup>4</sup>, Kenji Kawamura<sup>1†</sup> & Thomas F. Stocker<sup>1</sup>

Changes in past atmospheric carbon dioxide concentrations can be determined by measuring the composition of air trapped in ice cores from Antarctica. So far, the Antarctic Vostok and EPICA Dome C ice cores have provided a composite record of atmospheric carbon dioxide levels over the past 650,000 years<sup>1–4</sup>. Here we present results of the lowest 200 m of the Dome C ice core, extending the record of atmospheric carbon dioxide concentration by two complete glacial cycles to 800,000 yr before present. From previously published data<sup>1–8</sup> and the present work, we find that atmospheric carbon dioxide is strongly correlated with Antarctic temperature throughout eight glacial cycles but with significantly lower concentrations between 650,000 and 750,000 yr before present. Carbon dioxide levels are below 180 parts per million by volume (p.p.m.v.) for a period of 3,000 yr during Marine Isotope Stage 16, possibly reflecting more pronounced oceanic carbon storage. We report the lowest carbon dioxide concentration measured in an ice core, which extends the pre-industrial range of carbon dioxide concentrations during the late Quaternary by about 10 p.p.m.v. to 172–300 p.p.m.v.

Nature, 2008

Magic numbers:

172 ppm

300 ppm

# The global carbon cycle

Ocean is largest active C reservoir (38 000 Pg C; 50 x atm.)

C in ocean as

**DIC** = dissolved inorganic carbon (most),

**DOC** = dissolved organic carbon (quite a bit),

**POC** = particulate organic carbon (little, very active),

**PIC** = particulate inorganic carbon (even less;  $\text{CaCO}_3$  in the form of calcite or aragonite; ikaite).



# Marine Carbonate System: Concepts

Equilibrium coefficients, Bjerrum plot, pK value,  
Henry's law,

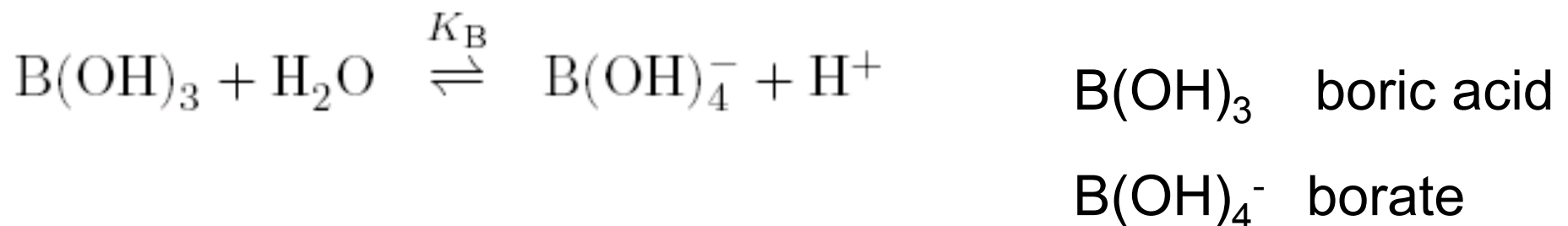
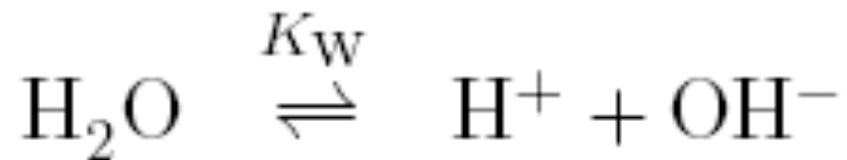
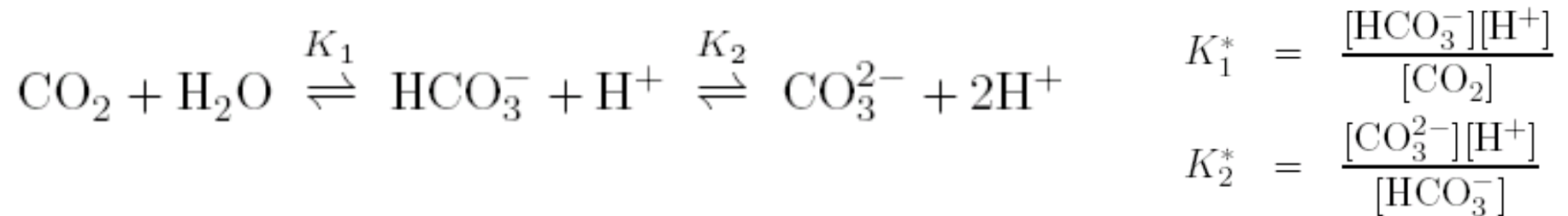
dissolved inorganic carbon (DIC), total alkalinity (TA),  
proton acceptors, proton donors, zero level of protons,  
conservative quantities,

buffering, Revelle factor,

nutrient-H<sup>+</sup>-compensation principle,

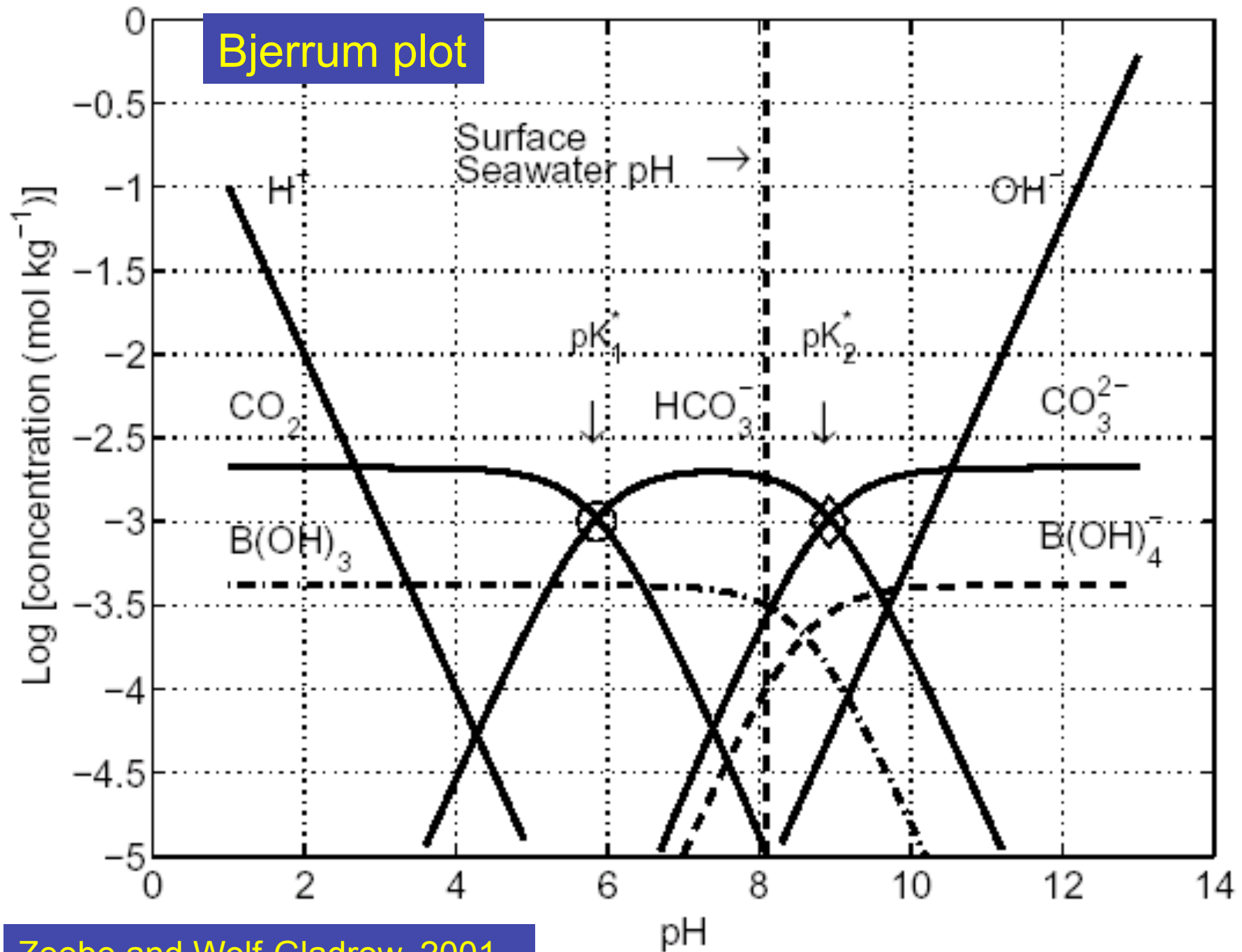
CaCO<sub>3</sub> precipitation and dissolution, lysocline, CCD.

# The carbonate system: equilibrium

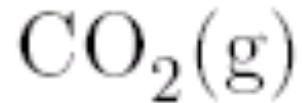


$$\text{p}K_1^* = -\log_{10} K_1^*$$

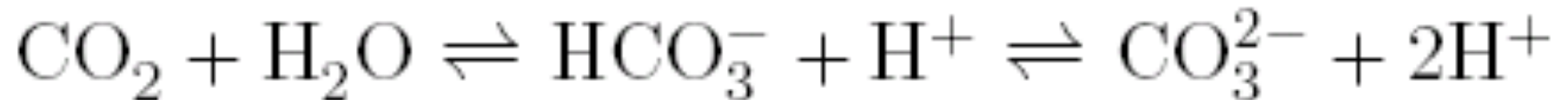
Bjerrum plot



# Atmosphere



air-sea equilibration is slow (compared to other gases such as  $\text{O}_2$ ,  $\text{N}_2$ ): several months



$$\begin{aligned} \text{DIC} &= \Sigma \text{CO}_2 = \text{total CO}_2 = \text{TCO}_2 \\ &= [\text{CO}_2] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \\ &\quad < 1\% \quad 90\% \quad 9\% \quad \text{at pH} = 8.2 \end{aligned}$$

Ocean



# Solubility of CO<sub>2</sub>: Henry's Law

In equilibrium the CO<sub>2</sub> concentration is proportional to the fugacity (Henry's law)

$$[\text{CO}_2] = K_0 \cdot f\text{CO}_2 \quad (\text{A.3.6})$$

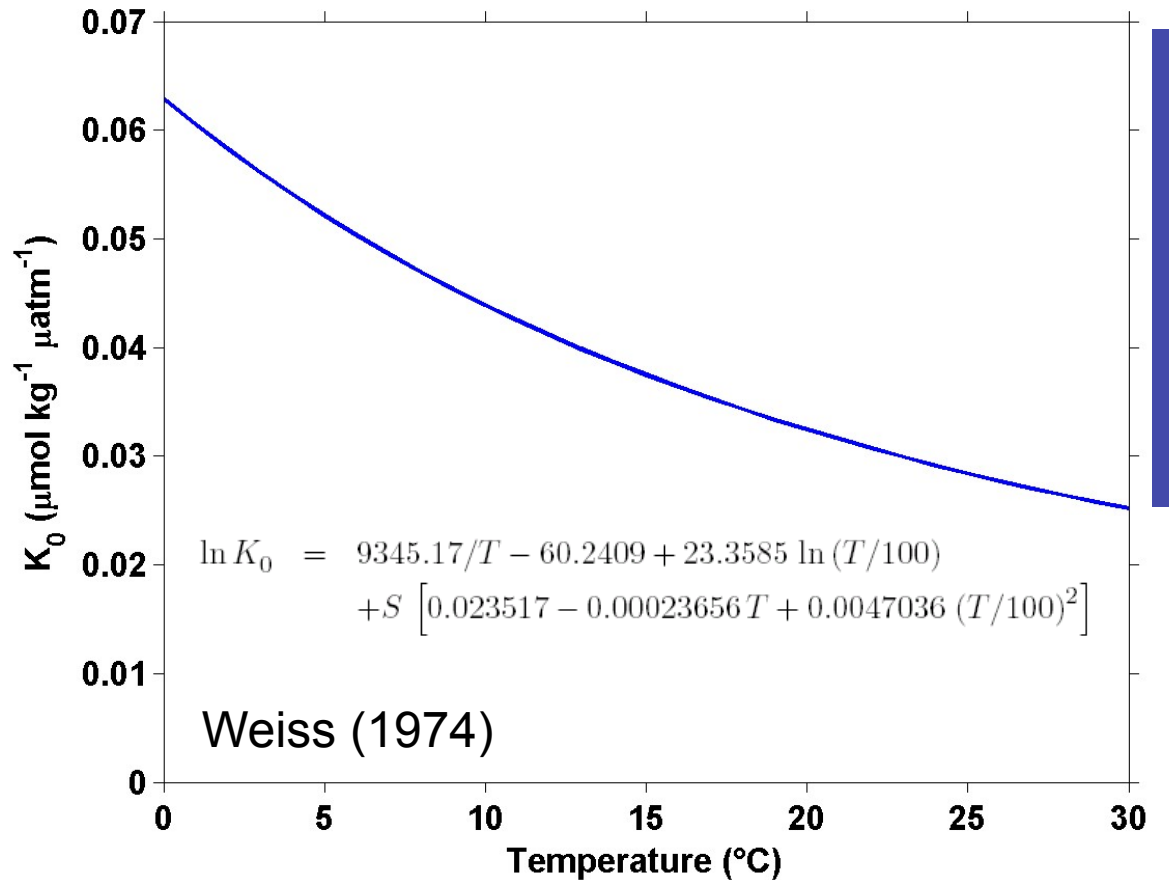
where  $K_0$  is Henry's constant. Units:  $[\text{CO}_2]$  in mol (kg-soln)<sup>-1</sup>,  $f\text{CO}_2$  in atm,  $K_0$  in mol (kg-soln)<sup>-1</sup> atm<sup>-1</sup>.

$$f\text{CO}_2 \approx p\text{CO}_2$$

fugacity

partial

pressure



$f\text{CO}_2 = 370 \mu\text{atm}$   
(atmospheric value, year 2000)

->

$[\text{CO}_2] (T_C = 0^\circ\text{C}) = 23 \mu\text{mol kg}^{-1}$   
 $[\text{CO}_2] (T_C = 25^\circ\text{C}) = 10 \mu\text{mol kg}^{-1}$

-> more CO<sub>2</sub> in cold water!

Units:

fugacity, partial pressure in atm

mixing ratio,  $x\text{CO}_2$  or  $\text{CO}_2$ , in ppm  
(parts per million)

# Total alkalinity

**“I found at least 20 different definitions of alkalinity!”**

An ocean carbon cycle modeler from Hamburg

**“... alkalinity, one of the most central but perhaps not the best understood concept in aquatic chemistry.”**

Morel and Hering (1993, p.157)

# Motivation

Total alkalinity (TA) and dissolved inorganic carbon (DIC) are used in all marine carbon cycle models because

- a) they are conservative (change in T, p; linear mixing relation) quantities and
- b) all other components of the marine carbonate system (i.e. the concentrations of  $\text{H}^+ \leftrightarrow \text{pH}$ ,  $\text{OH}^-$ ,  $\text{CO}_2$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ) can be calculated using TA and DIC (given T,S,p).

The change of pH,  $\text{CO}_2$  and other quantities due to certain biogeochemical processes (as, for example,  $\text{CaCO}_3$  precipitation or methane oxidation combined with sulfate reduction) can be calculated using TA.

# A verbal definition of TA

Total alkalinity (TA) is the excess of proton acceptors over proton donors with respect to a zero level of protons.

$H^+$  = proton (chemical slang)

Proton acceptors:  $HCO_3^-$ ,  $CO_3^{2-}$ , ...

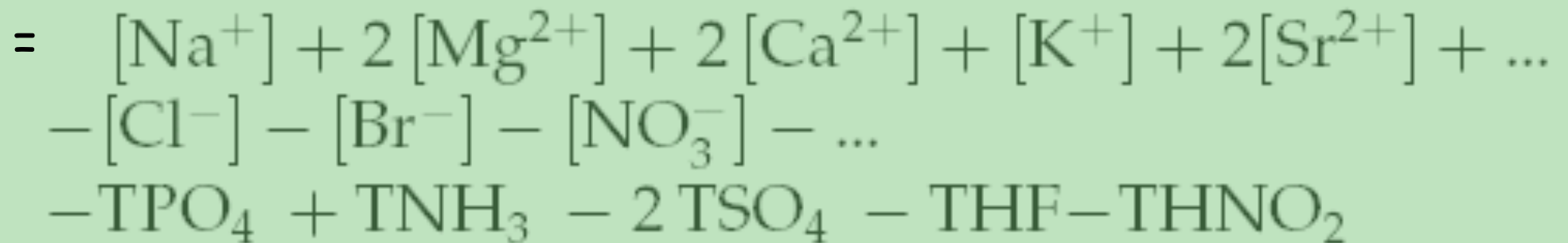
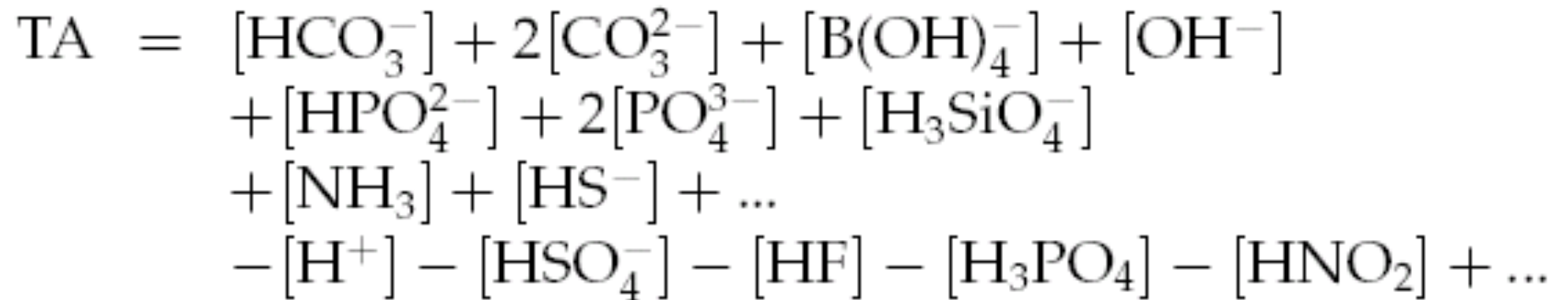
Proton donors:  $H_3PO_4$ , ...

Zero level of protons: dominant chemical species at  $pH = 4.5$

Add strong acid (HCl) to seawater: pH decreases slightly because most  $H^+$  combine with proton acceptors (pH buffer).  
TA measures buffer capacity.



# TA in seawater: two equivalent expressions



# Total alkalinity: The explicit conservative expression and its application to biogeochemical processes

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Arne Körtzinger<sup>a,2</sup>, Andrew G. Dickson<sup>a,b</sup>

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Received 13 February 2006; received in revised form 15 September 2006; accepted 4 January 2007

Available online 26 January 2007

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## Abstract

Total alkalinity (TA) is one of the few measurable quantities that can be used together with other quantities to calculate concentrations of species of the carbonate system ( $\text{CO}_2$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{H}^+$ ,  $\text{OH}^-$ ). TA and dissolved inorganic carbon (DIC) are conservative quantities with respect to mixing and changes in temperature and pressure and are, therefore, used in oceanic carbon cycle models. Thus it is important to understand the changes of TA due to various biogeochemical processes such as formation and remineralization of organic matter by microalgae, precipitation and dissolution of calcium carbonate. Unfortunately deriving such changes from the common expression for TA in terms of concentrations of non-conservative chemical species ( $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{B}(\text{OH})_4^-$ ,  $\text{H}^+$ ,  $\text{OH}^-$ , etc.) is rarely obvious.

Here an expression for TA ( $\text{TA}_{\text{ec}}$ ) in terms of the total concentrations of certain major ions ( $\text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$  etc.) and the total concentrations of various acid-base species (total phosphate etc.) is derived from Dickson's original definition of TA under the constraint of electroneutrality. Changes of TA by various biogeochemical processes are easy to derive from this so-called explicit conservative expression for TA because each term in this expression is independent of changes of temperature or pressure within the ranges normally encountered in the ocean and obeys a linear mixing relation.

Further, the constraints of electroneutrality for nutrient uptake by microalgae and photoautotrophs are discussed. A so-called *nutrient- $\text{H}^+$ -compensation principle* is proposed. This principle in combination with  $\text{TA}_{\text{ec}}$  allows one to make predictions for changes in TA due to uptake of nutrients that are consistent with observations. A new prediction based on this principle is the change in TA due to nitrogen fixation followed by remineralization of organic matter and subsequent nitrification of ammonia which implies a significant sink of TA in tropical and subtropical regions where most of the nitrogen fixation takes place.

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**Marine Chemistry 106 (2007) 287–300**

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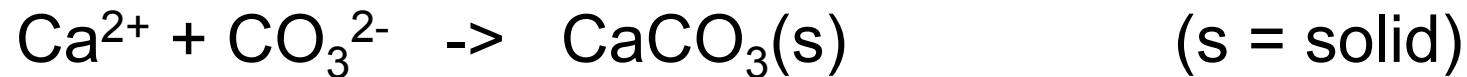
*Keywords:* Proton acceptors; Proton condition; Electroneutrality; Calcification; Nitrogen fixation; Remineralization

---

Uptake or release of  $\text{CO}_2$   
by the ocean  
-> no change in TA

However: change of pH (‘acidification of the ocean’)

# CaCO<sub>3</sub> precipitation



or



Both reaction schemes are stoichiometrically correct, i.e. they conserve chemical elements and electric charge.

The second scheme suggests creation of CO<sub>2</sub> which is not the case for the first scheme. Which one is right?

Answer: Neither the first nor the second reaction scheme tells the whole story!

# CaCO<sub>3</sub> ...

1. scheme: CO<sub>3</sub><sup>2-</sup> is used -> shift of carbonate equilibrium towards lower pH (less CO<sub>3</sub><sup>2-</sup>) and thus more CO<sub>2</sub>. The CO<sub>2</sub> is created via 2 HCO<sub>3</sub><sup>-</sup> -> CO<sub>2</sub> + CO<sub>3</sub><sup>2-</sup> + H<sub>2</sub>O, i.e. CO<sub>3</sub><sup>2-</sup> is (partially) resupplied.

2. scheme: CO<sub>2</sub> is created -> shift to lower pH (more CO<sub>2</sub>). The created CO<sub>2</sub> is (partially) converted to HCO<sub>3</sub><sup>-</sup> via CO<sub>2</sub> + CO<sub>3</sub><sup>2-</sup> + H<sub>2</sub>O -> 2 HCO<sub>3</sub><sup>-</sup>, i.e. the concentration of CO<sub>3</sub><sup>2-</sup> decreases.

-> increase of [CO<sub>2</sub>] and decrease [CO<sub>3</sub><sup>2-</sup>] in both cases (qualitative statement).

# CaCO<sub>3</sub> ...

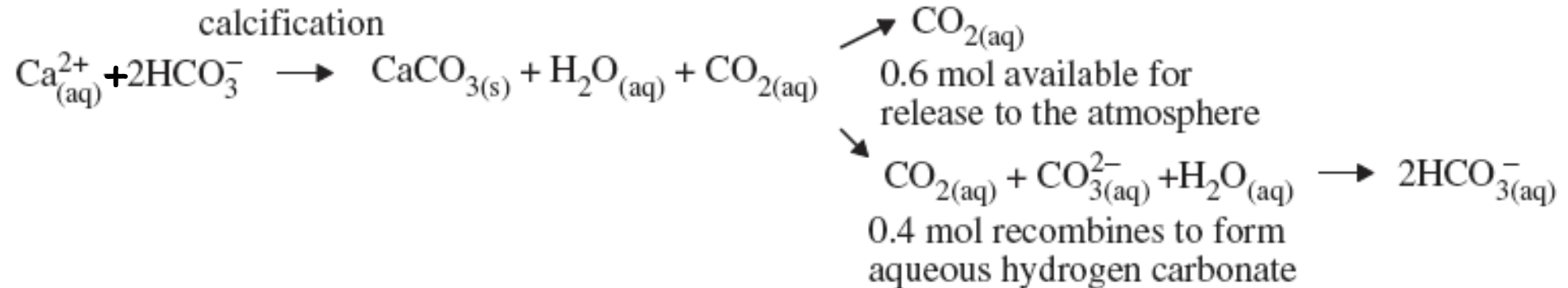
Independent of the reaction scheme:

Change of DIC: DIC decreases by 1 mole per mole  
CaCO<sub>3</sub> precipitated

Change of TA: TA decreases by 2 moles per mole  
CaCO<sub>3</sub> precipitated (TA<sup>(ec)</sup> contains  
the term 2 [Ca<sup>2+</sup>] but neither of the  
other chemical species in the reaction  
schemes or in the consecutive buffer  
reactions.)

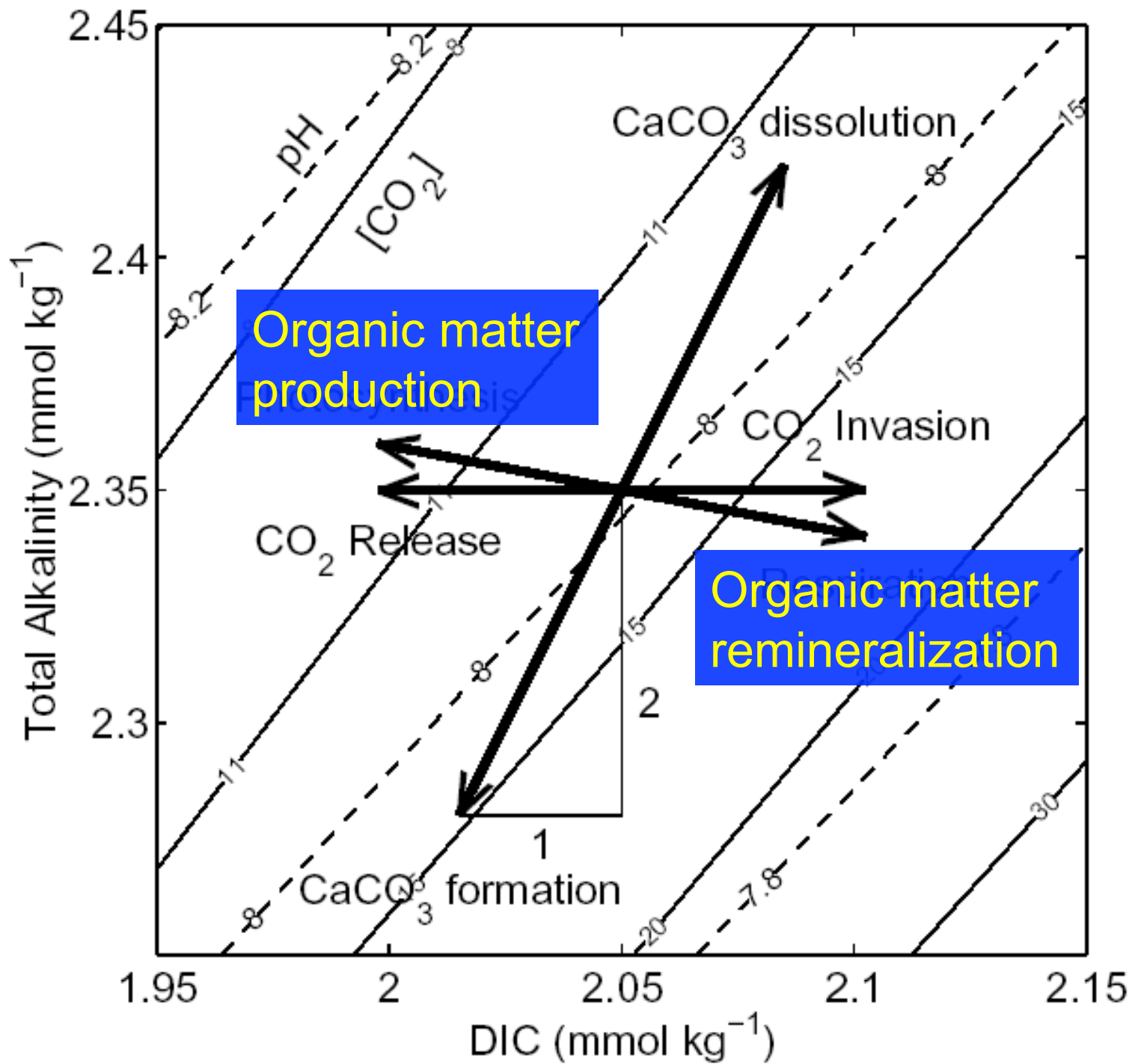


# Calcification



Rees et al., 2005

Remark: 0.6:0.4 splitting is typical for seawater; exact ratio depends on parameters of marine carbonate system (DIC, TA, T, S).



$[\text{CO}_2]$  in  $\mu\text{mol kg}^{-1}$

Zeebe and Wolf-Gladrow, 2001

# TA changes mainly due to ...

## **TA changes with salinity.**

Exercise: Explain why and how?

CaCO<sub>3</sub> precipitation (-2) or dissolution (+2)

NO<sub>3</sub><sup>-</sup> assimilation (+1) by microalgae

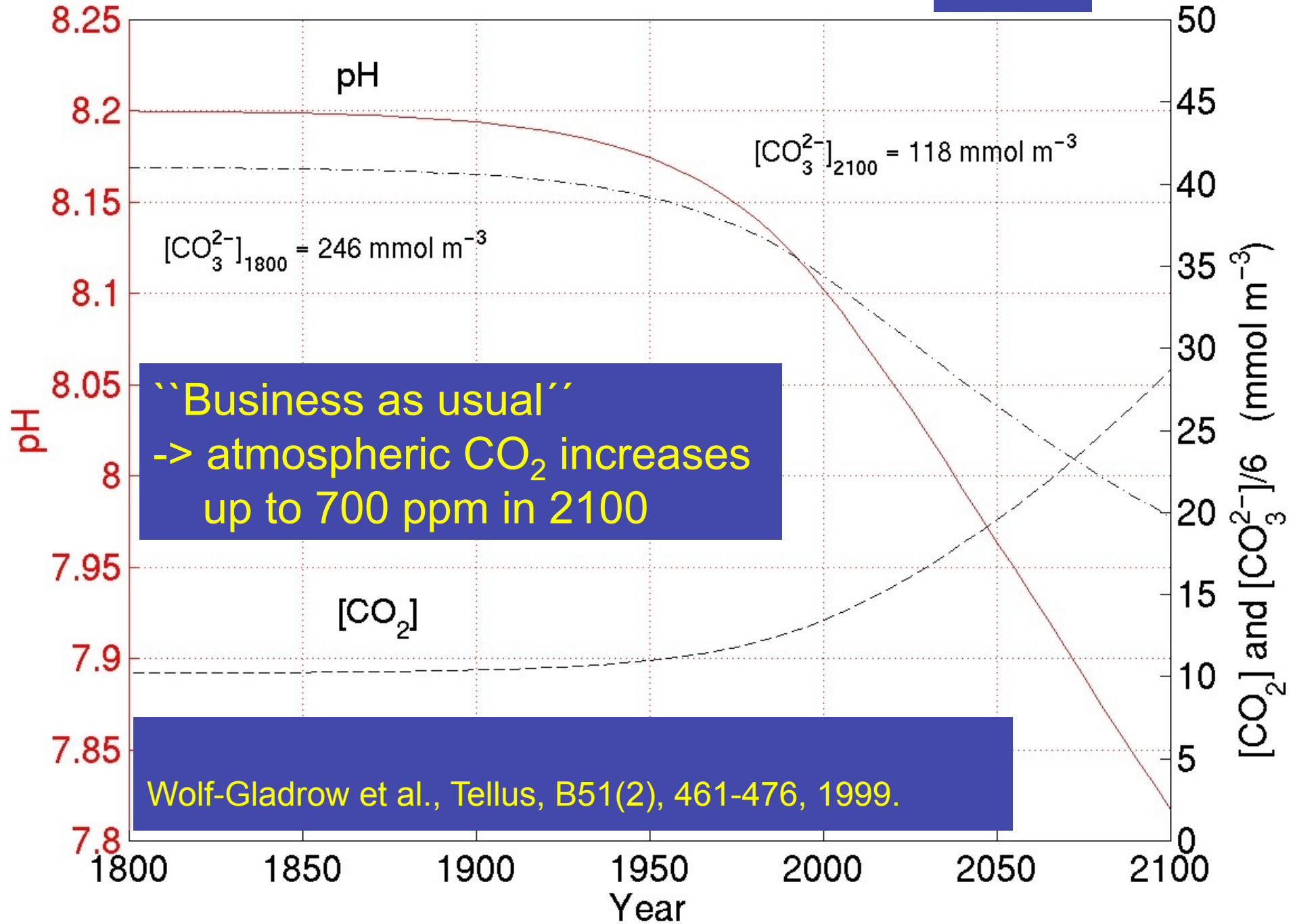
... many other biogeochemical processes ...  
(Wolf-Gladrow et al., Marine Chemistry, 2007)

# Ocean acidification

The term 'ocean acidification' has been coined by Caldeira, K.; Wickett, M.E. (2003). "Anthropogenic carbon and ocean pH". *Nature* 425 (6956): 365–365. doi:10.1038/425365a

# Ocean acidification

Future



# A simple question ...

Suppose the  $\text{CO}_2$  concentration in the atmosphere doubles.  
How would DIC change in the surface ocean?

Remark: to keep it simple we neglect any response by organisms or sediments.

Answer 1: doubling of DIC, i.e. from 2 to 4  $\text{mmol kg}^{-1}$ .

Answer 2: doubling of  $\text{CO}_2$  in the water,  $\text{CO}_2$  contributes about 1% of DIC  $\rightarrow$  DIC increases from 2 to 2.02  $\text{mmol kg}^{-1}$ .

Answers are quite different.

**Both answers are wrong! DIC will increase by  $\approx 10\%$ .**

( $\rightarrow$  Revelle factor)



# DIC in the ocean

How is DIC distributed in the ocean?

How to explain this distribution?

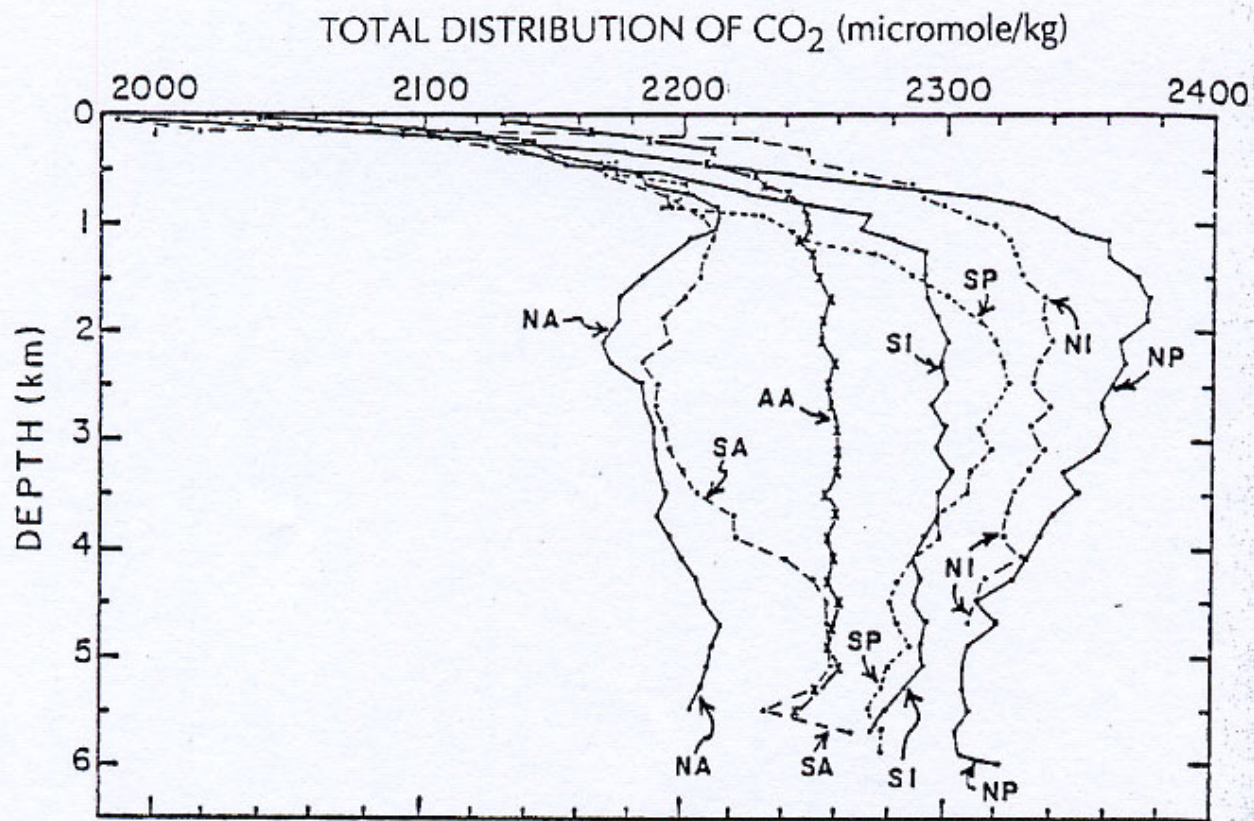


Figure 1. Depth distribution of the total CO<sub>2</sub> concentration in the global oceans. NA & SA = North & South Atlantic; NP and SP = North and South Pacific; NI and SI = North and South Indian Oceans; and AA = Antarctic ocean.

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

# The biological carbon pumps

- 1. Soft tissue pump:** production of particulate organic matter (POM) in surface ocean by microalgae and cyanobacteria; foodchain; physical aggregation; ... ; sinking of POM out of surfacelayer (‘export production’); remineralization in deeper layers by zooplankton and bacteria: release of CO<sub>2</sub> (and nutrients); small effect on TA.
- 2. CaCO<sub>3</sub> pump:** precipitation of CaCO<sub>3</sub> by coccolithophores, foraminifera, pteropods, ...; export to deep ocean and sediments; strong impact on TA.

Pump: transport against DIC concentration gradient.

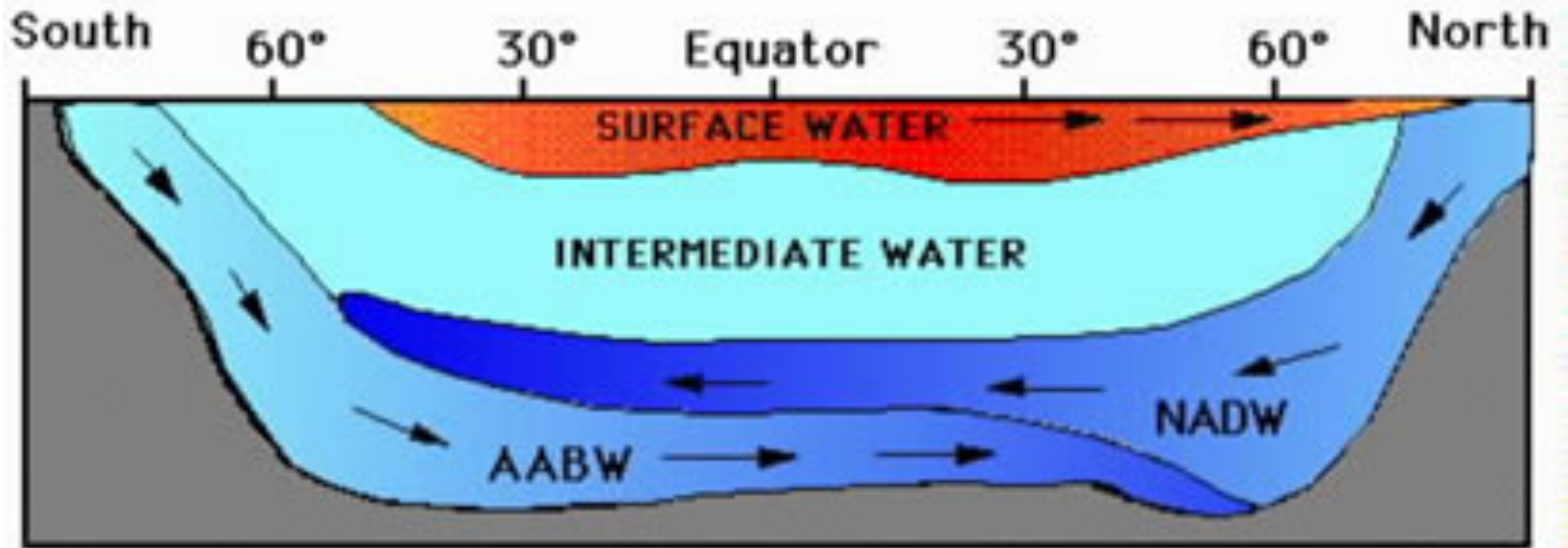
# The physical carbon pump

Solubility of CO<sub>2</sub> increases strongly with decreasing temperatures --> more CO<sub>2</sub> and DIC in cold water.

Surface ocean is mostly warm (‘warm water sphere’).

However, most of the ocean is cold: deep waters are formed at high latitudes; cold surface waters contain high concentrations of gases; gas-rich water is distributed by ocean circulation --> huge layer of cold CO<sub>2</sub>-rich water below thin warm layer with less CO<sub>2</sub>.

# Atlantic Ocean Thermohaline Circulation



Increased nutrients & dissolved CO<sub>2</sub>

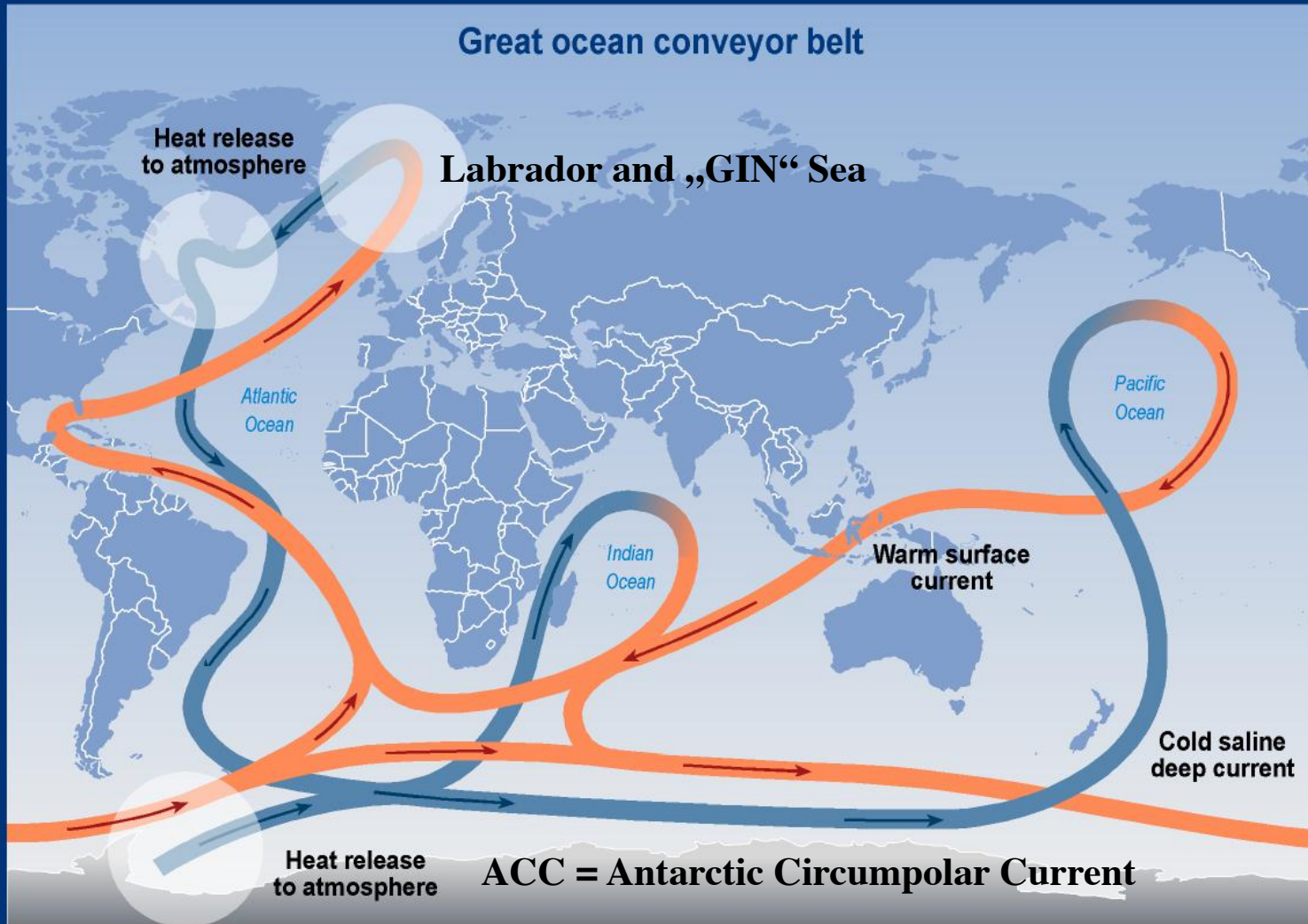


Warm, low nutrients, & oxygenated



[oceanography.geol.ucsb.edu/~gs4/Mini\\_Studies/Deep\\_Ocean\\_Circulation/Deep\\_Ocean\\_Circulation\\_files/image003.jpg](http://oceanography.geol.ucsb.edu/~gs4/Mini_Studies/Deep_Ocean_Circulation/Deep_Ocean_Circulation_files/image003.jpg)





SYR - FIGURE 4-2

IPCC

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

1000 a





# Deconstructing the Conveyor Belt

M. Susan Lozier

For the past several decades, oceanographers have embraced the dominant paradigm that the ocean's meridional overturning circulation operates like a conveyor belt, transporting cold waters equatorward at depth and warm waters poleward at the surface. Within this paradigm, the conveyor, driven by changes in deepwater production at high latitudes, moves deep waters and their attendant properties continuously along western boundary currents and returns surface waters unimpeded to deepwater formation sites. A number of studies conducted over the past few years have challenged this paradigm by revealing the vital role of the ocean's eddy and wind fields in establishing the structure and variability of the ocean's overturning. Here, we review those studies and discuss how they have collectively changed our view of the simple conveyor-belt model.

Science 2010

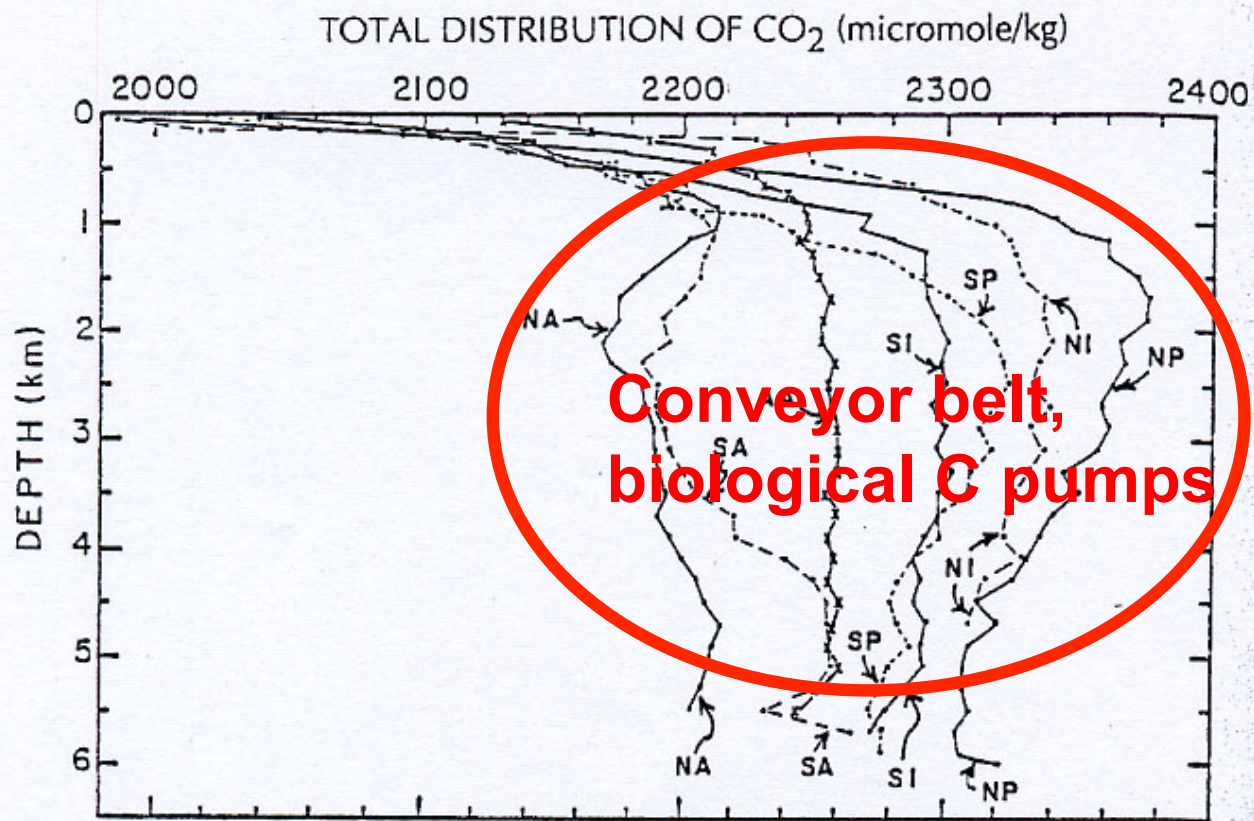


Figure 1. Depth distribution of the total  $\text{CO}_2$  concentration in the global oceans. NA & SA = North & South Atlantic; NP and SP = North and South Pacific; NI and SI = North and South Indian Oceans; and AA = Antarctic ocean.

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

The observed distributions of DIC in the ocean can be explained by a combination of the physical (solubility) and the biological (soft-tissue and  $\text{CaCO}_3$ ) carbon pumps.

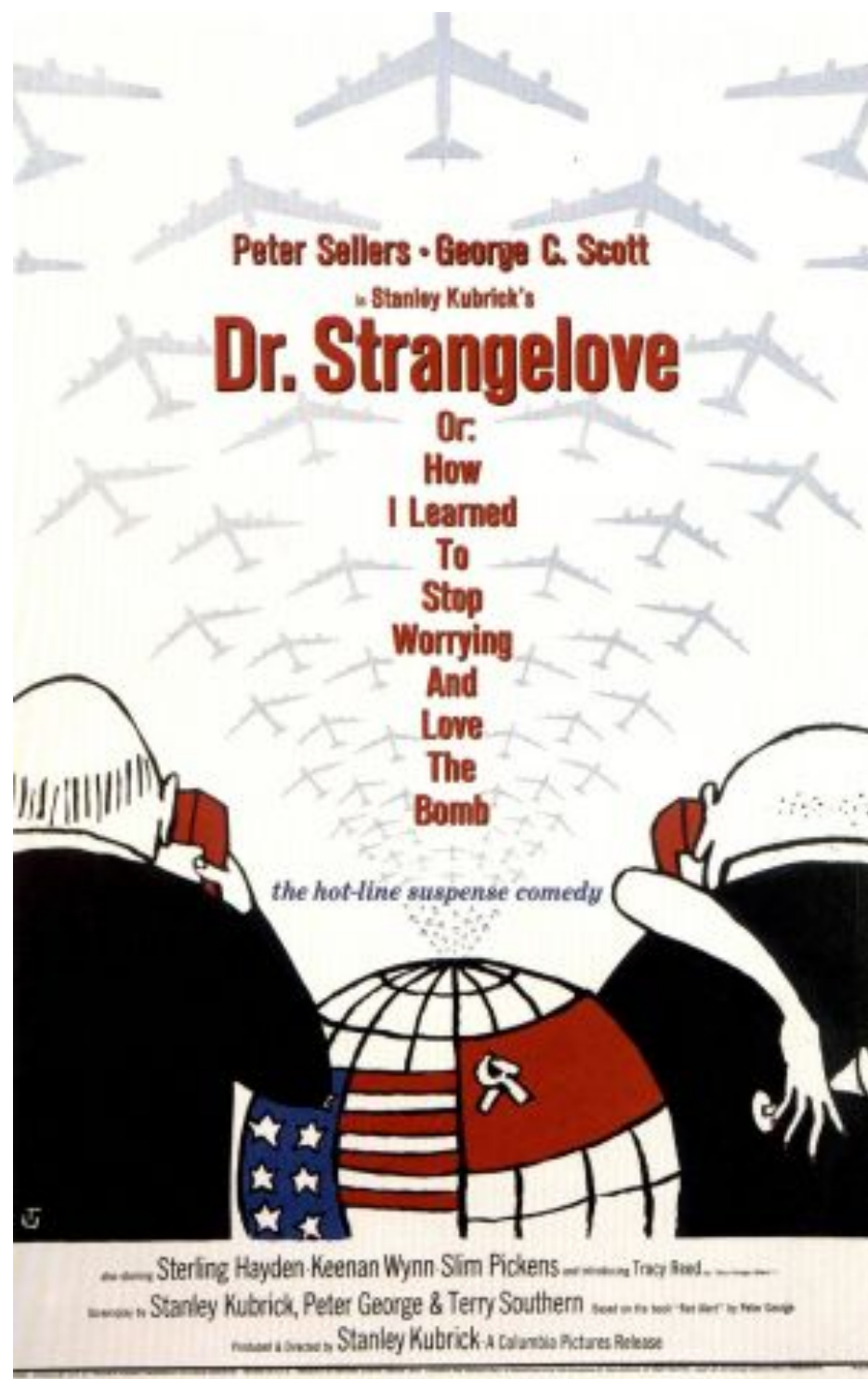
How important are the biological pumps?

Let's ask ...



Dr. Strangelove





2.2.2011

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## What happens if biology is turned off?

The biological pumps stop.

The surface-to-deep DIC and CO<sub>2</sub> gradients decrease.

**Within 250 years atmospheric CO<sub>2</sub> doubles.**

see: Maier-Reimer, Mikolajewicz and Winguth (1996); Zeebe and Westbroek (2003)

The global carbon cycle is largely driven by circulation and biology.

On glacial-interglacial timescales, atmospheric CO<sub>2</sub> is slave to the average oceanic surface [CO<sub>2</sub>]!

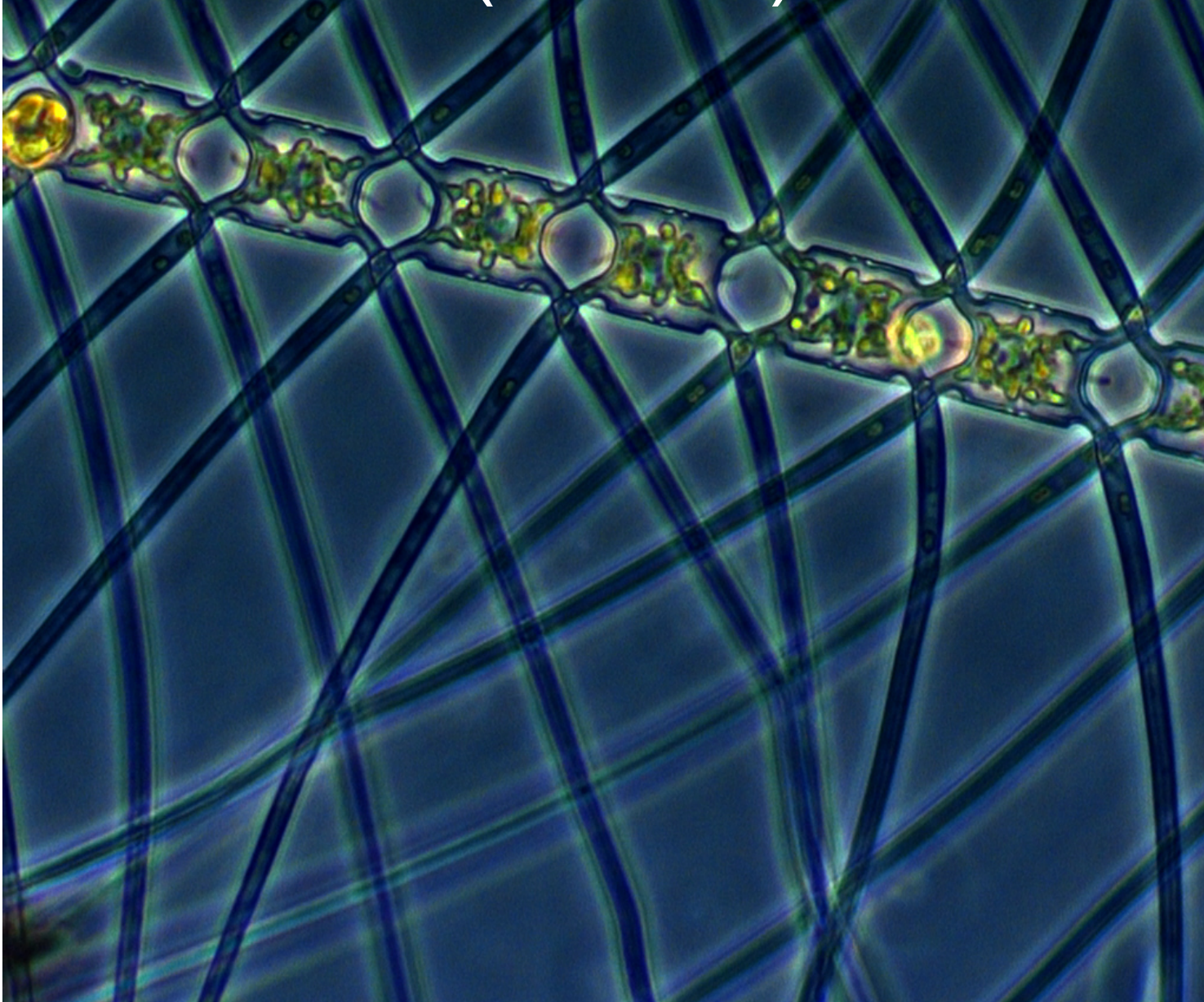


# Which organisms drive the pumps?

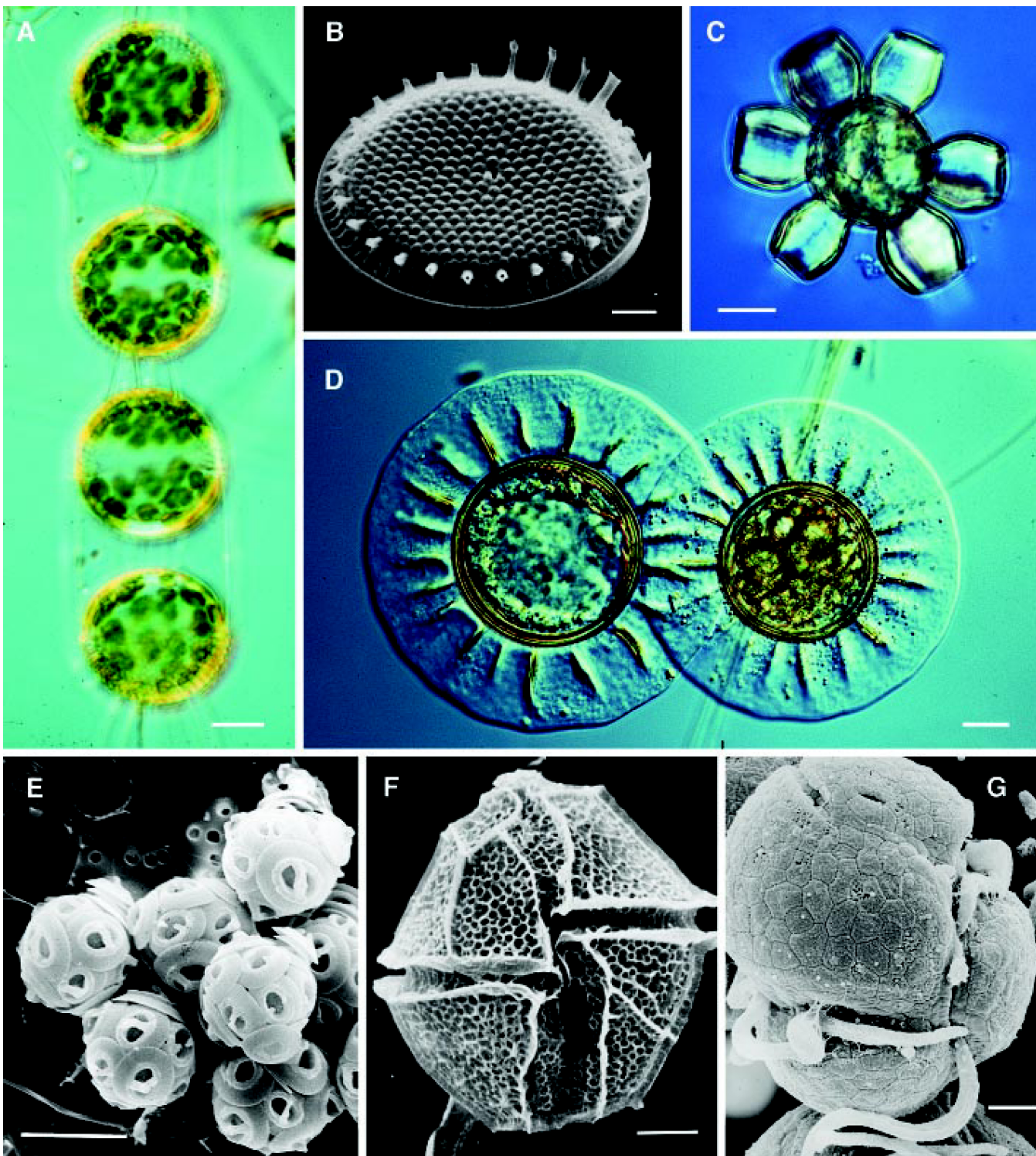
Microalgae (size 1/100 to 1/10 mm)

Zooplankton (1/10 to 100 mm)

# *Chaetoceros atlanticus* (diatom)



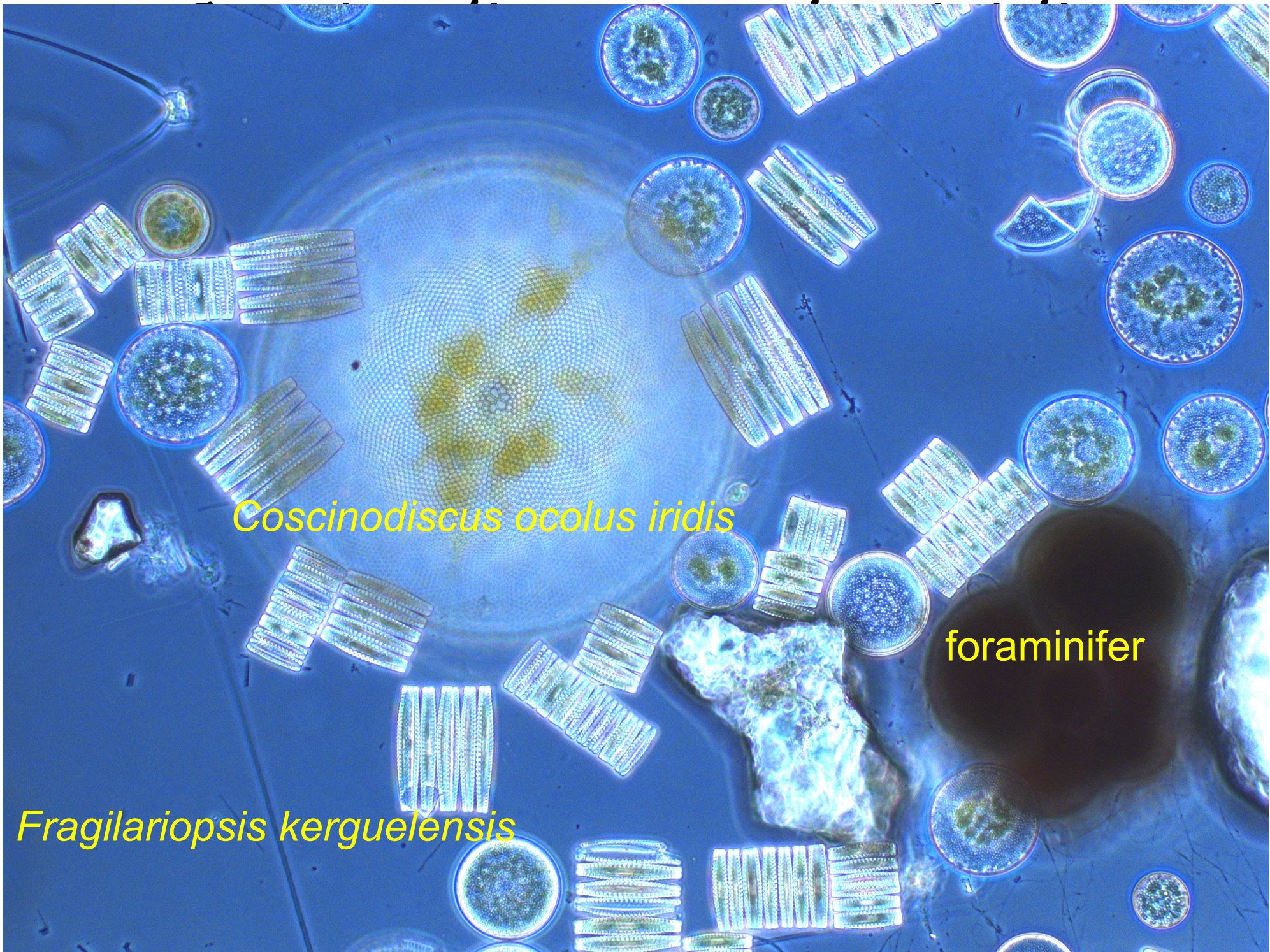




**Fig. 1.** Examples of representative marine eukaryotic phytoplankton. (A) A chain of the diatom *Stephanopyxis nipponica*. (B) A single valve of the diatom *Thalassiosira pacifica*. (C) The large, tropical coccolithophore *Scyphospahaera apsteinii*. (D) An overlapping pair of phycomas of *Pterosperma moebii*. (E) A clump of coccospheres of *Gephyrocapsa oceanica*. (F) The athecate dinoflagellate *Karlodinium micrum* (*Gyrodinium galatheanum*). (G) The thecate dinoflagellate *Lingulodinium polyedra*. Scale bars: (A, C, E, F) 10  $\mu\text{m}$ ; (B and G) 2  $\mu\text{m}$ ; and (D) 25  $\mu\text{m}$ .

Falkowski et al., Science, 2004.



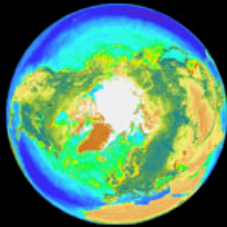
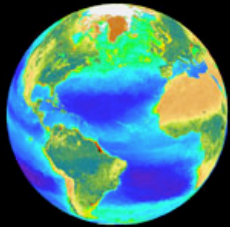


*Coscinodiscus oculus iridis*

*Fragilariopsis kerguelensis*

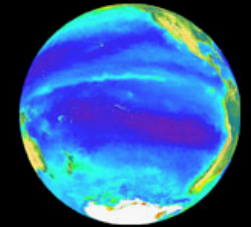
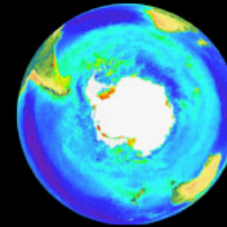
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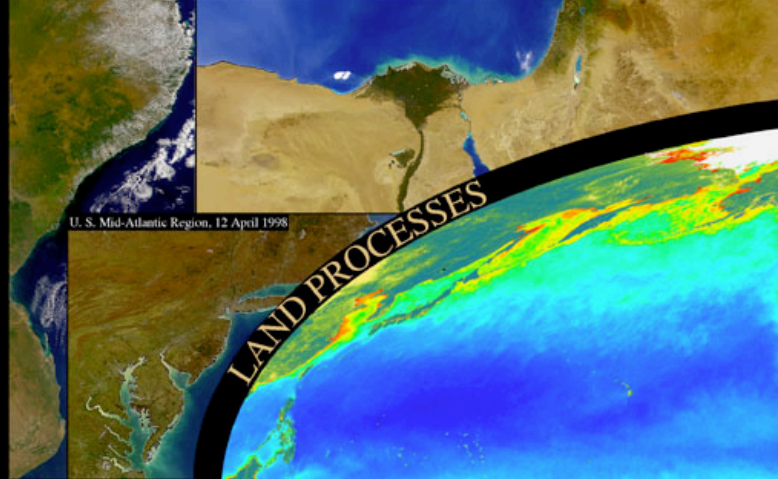


# SeaWiFS Project

<http://seawifs.gsfc.nasa.gov/seawifs.html>



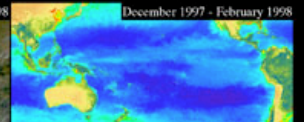
East Coast of Africa, 19 July 1998 Eastern Mediterranean and the Nile River Delta, 6 April 1998



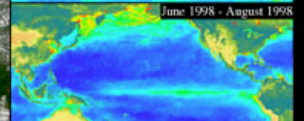
## NASA/GSFC



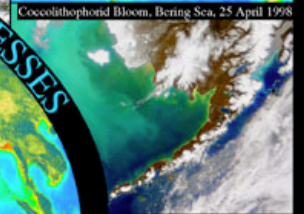
Coccolithophorid Bloom, Bay of Biscay, Celtic Sea, 18 May 1998



December 1997 - February 1998



June 1998 - August 1998

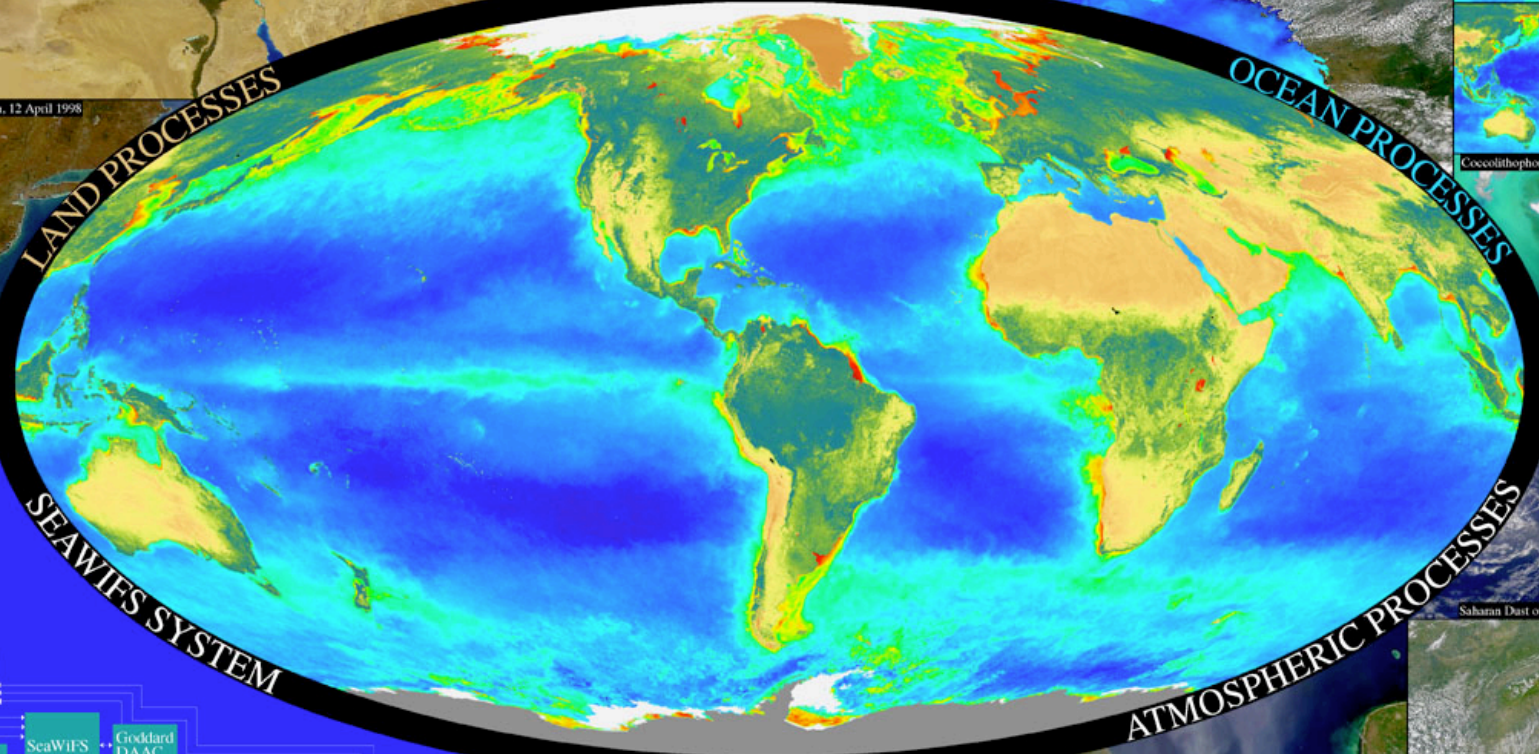


Coccolithophorid Bloom, Bering Sea, 25 April 1998

U.S. Mid-Atlantic Region, 12 April 1998

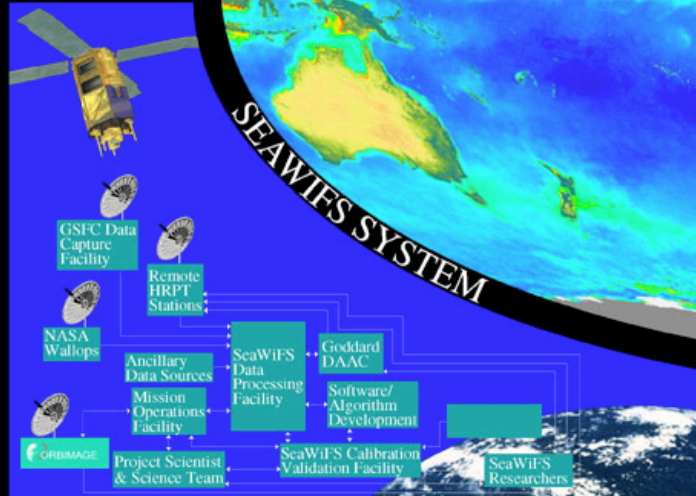
LAND PROCESSES

OCEAN PROCESSES

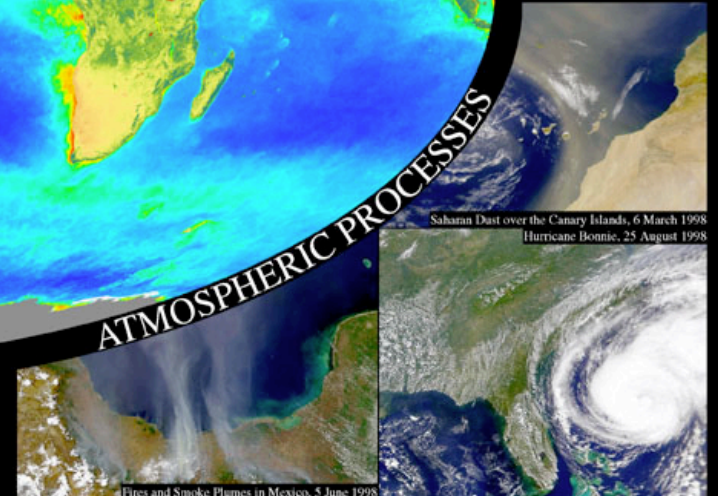


SEAWIFS SYSTEM

ATMOSPHERIC PROCESSES



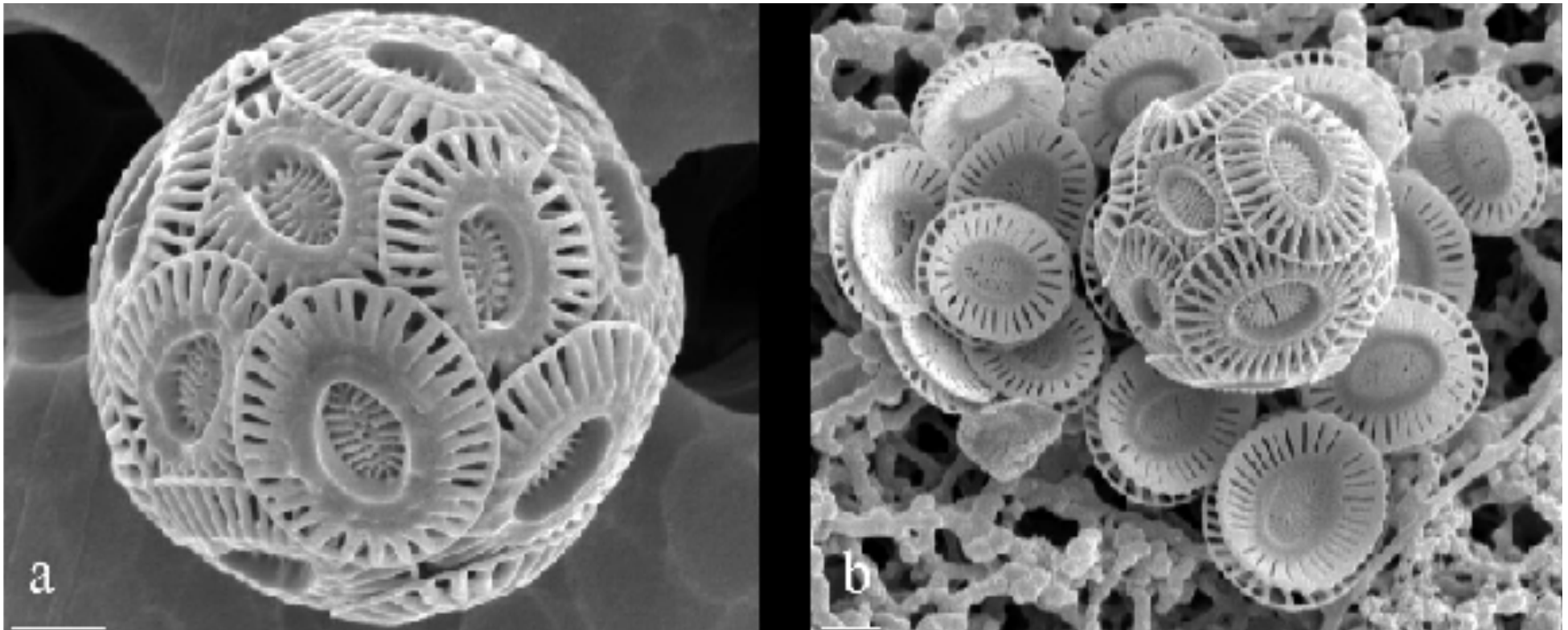
Maximum Minimum  
Land: Normalized Difference Vegetation Index  
Ocean: Chlorophyll *a* Concentration (mg/m<sup>3</sup>)



Saharan Dust over the Canary Islands, 6 March 1998  
Hurricane Bonnie, 25 August 1998

Fires and Smoke Plumes in Mexico, 5 June 1998

# *Emiliana huxleyi*



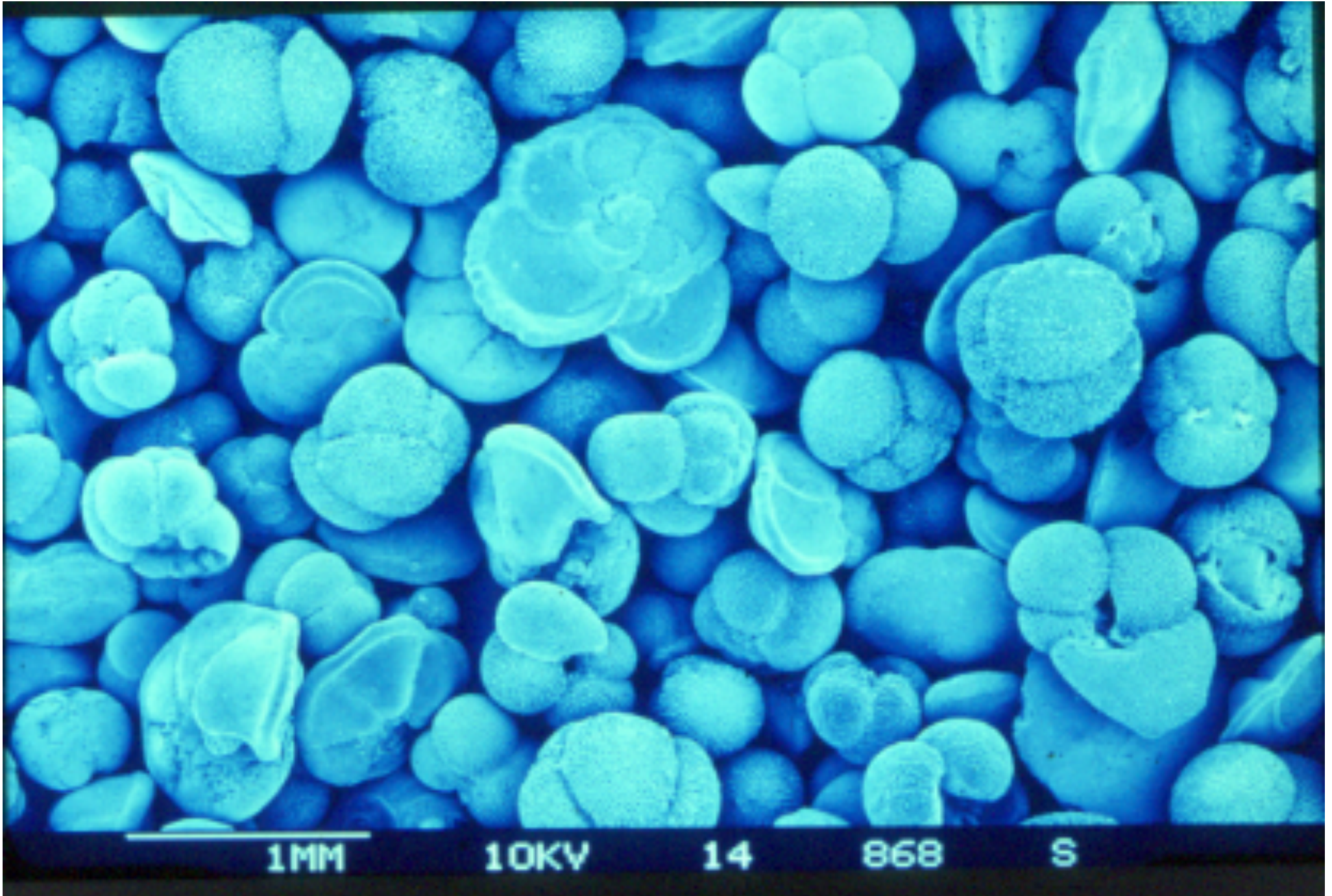
(Toby Tyrrell)





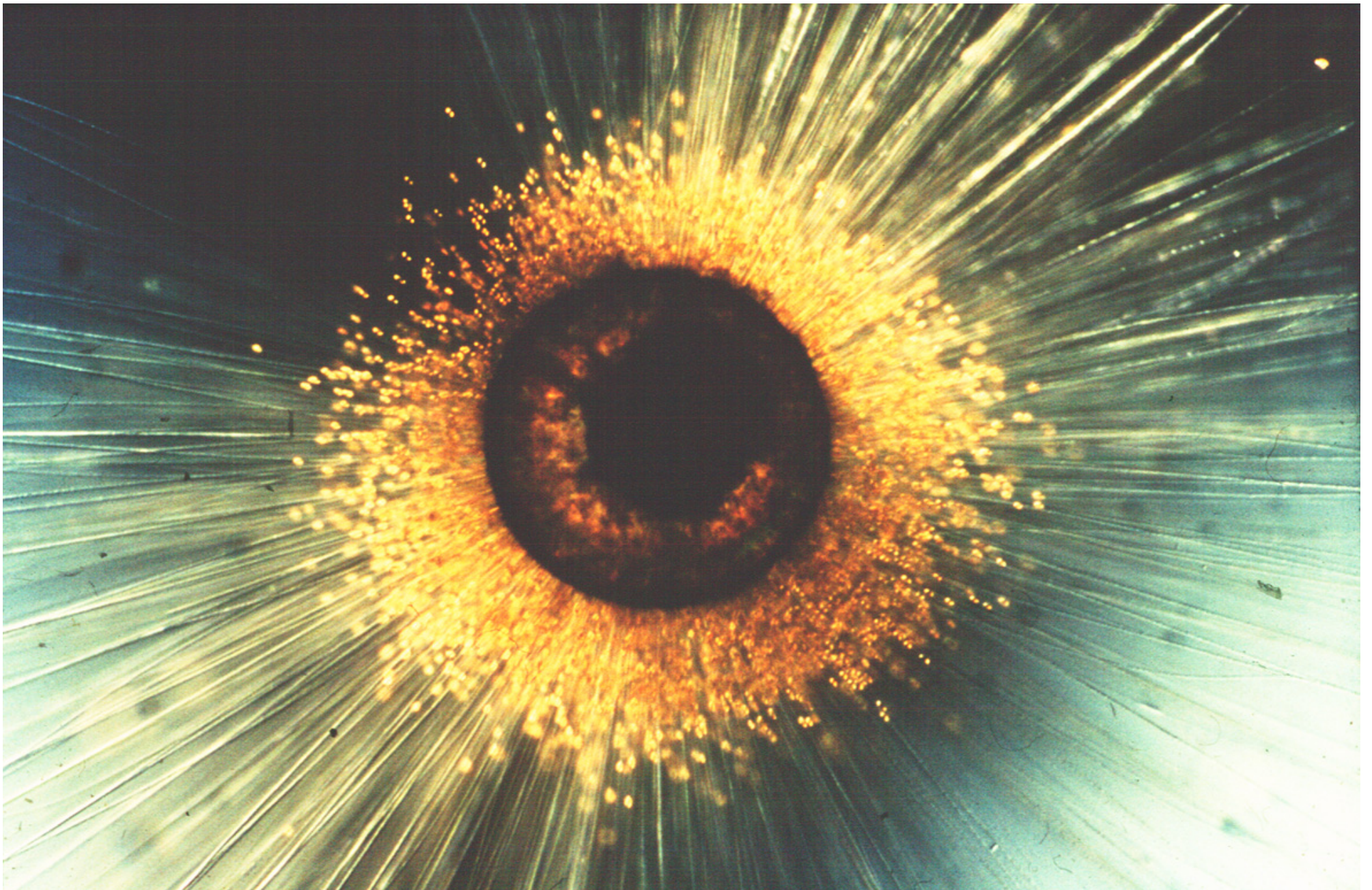


... only a dead foram is a good foram!

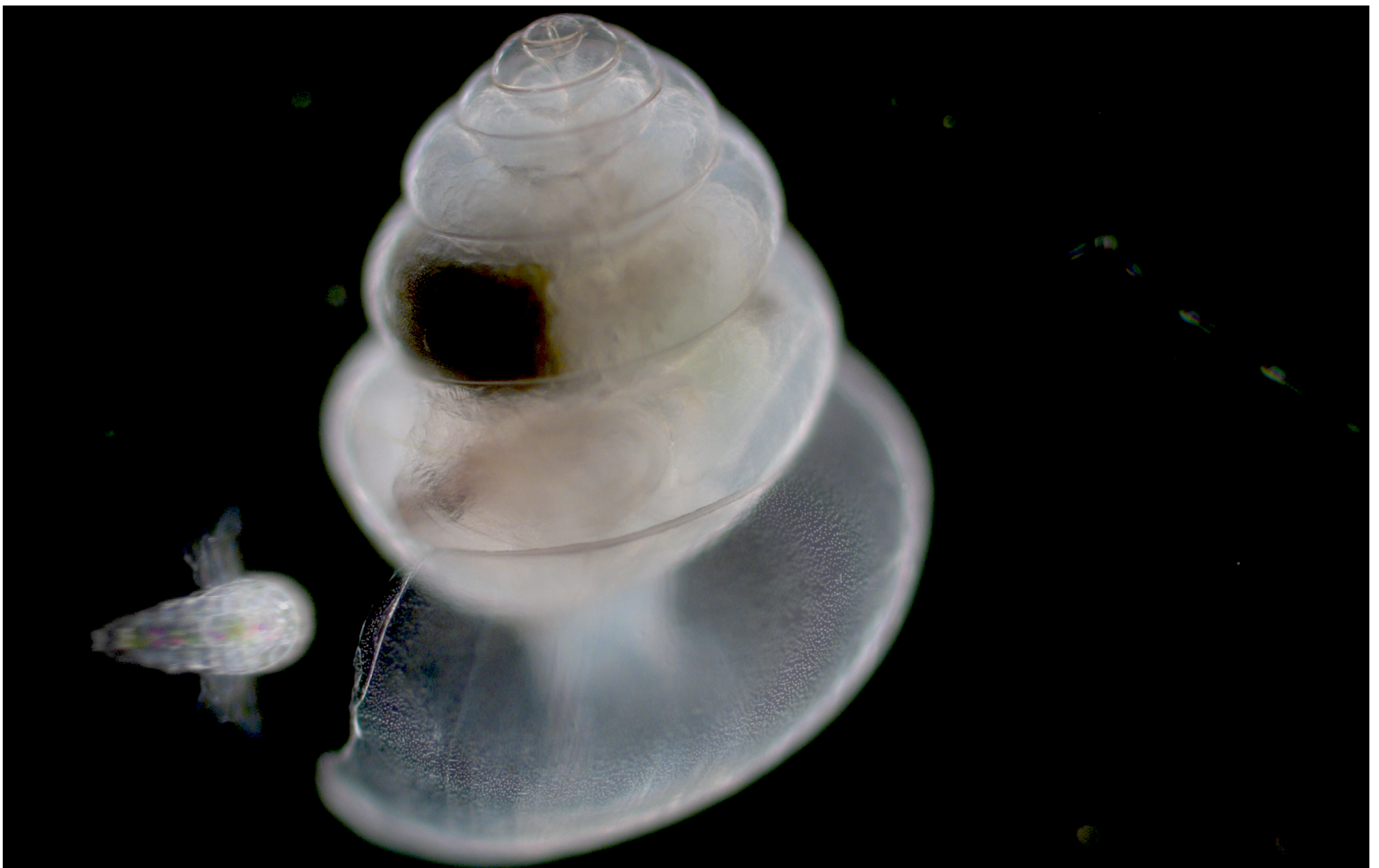




# *Orbulina universa*







Copepod (left) and pteropod *Limacina retroversa australis* (ca. 2 mm)

(Foto: Wolf-Gladrow)

# Organisms couple the cycles of C, N, P, S, O<sub>2</sub>, Si, Ca, Fe, Zn, ...

Phytoplankton and zooplankton show mean molar ratios  
C:N:P = 106:16:1 (Redfield 1934, 1963).

Explanation: All organisms consist mainly of proteins,  
lipids, carbohydrates, and water. They differ in the  
type and amount of biominerals.

Most important biominerals in plankton: CaCO<sub>3</sub>, SiO<sub>2</sub>

Metals (Fe, Zn, Co, ...) are required for metallo-enzymes.

# Consequences of coupling

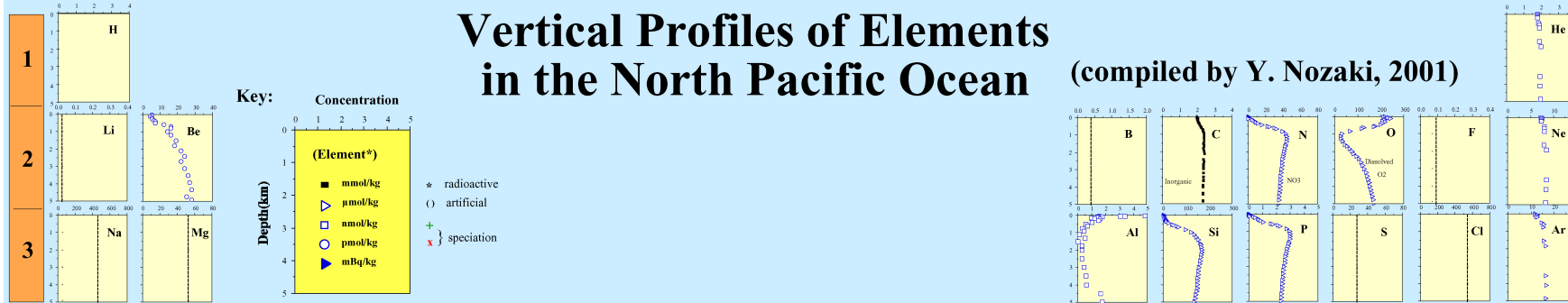
Biological carbon pumps --> **biological pump** (C, N, P, Si, ...)

The global carbon cycle cannot be understood or simulated without taking into account the cycles of other elements.



# Vertical Profiles of Elements in the North Pacific Ocean

(compiled by Y. Nozaki, 2001)



1A 2A 3A 4A 5A 6A 7A 8 1B 2B 3B 4B 5B 6B 7B 0



# Take-Home Message

Climate change is a major motivation

Natural variations, anthropogenic perturbations

Carbon cycle: 4 active reservoirs, large natural fluxes, DIC + TA  
(conservative quantities), physical + biological carbon pumps, ...

Coupling of elemental cycles by organisms:  
C, N, P, O, S, Ca, Si, Fe, Zn, ...

# References/Further Reading

Broecker and Peng, Tracers in the Sea, 1982.

Frausto da Silva and Williams, The Biological Chemistry of the Elements, 2nd edition, 2001.

Schulze, E.-D., M. Heimann, S. Harrison, E. Holland, J. Lloyd, C. Prentice, and D. Schimel (eds.): Global Biogeochemical Cycles in the Climate System, Academic Press, San Diego, 350 pp. 2001.

Fasham, M.J.R. (ed.), Ocean Biogeochemistry, Springer, 2003.

Schlesinger, W.H. (ed.): Biogeochemistry, Elsevier, 702 pp., 2005.

# References/Further Reading II

Zeebe, R.E., and D. Wolf-Gladrow, CO<sub>2</sub> in Seawater: Equilibrium, Kinetics, Isotopes, Elsevier, 346 pp, 2001 (reprinted 2005).

Sarmiento, J.L. and N. Gruber, Ocean Biogeochemical Dynamics, Princeton University Press, Princeton and Oxford, 2006.

Emerson, S.R. and J.I. Hedges, Chemical Oceanography and the Marine Carbon Cycle, Cambridge U.P., 2008.

IPCC, Fourth Assessment Report: book or [www.ipcc.ch](http://www.ipcc.ch).

# The End

Thanks for your attention

# Definitions: GPP, $R_A$ , NPP

Primary production (PP):

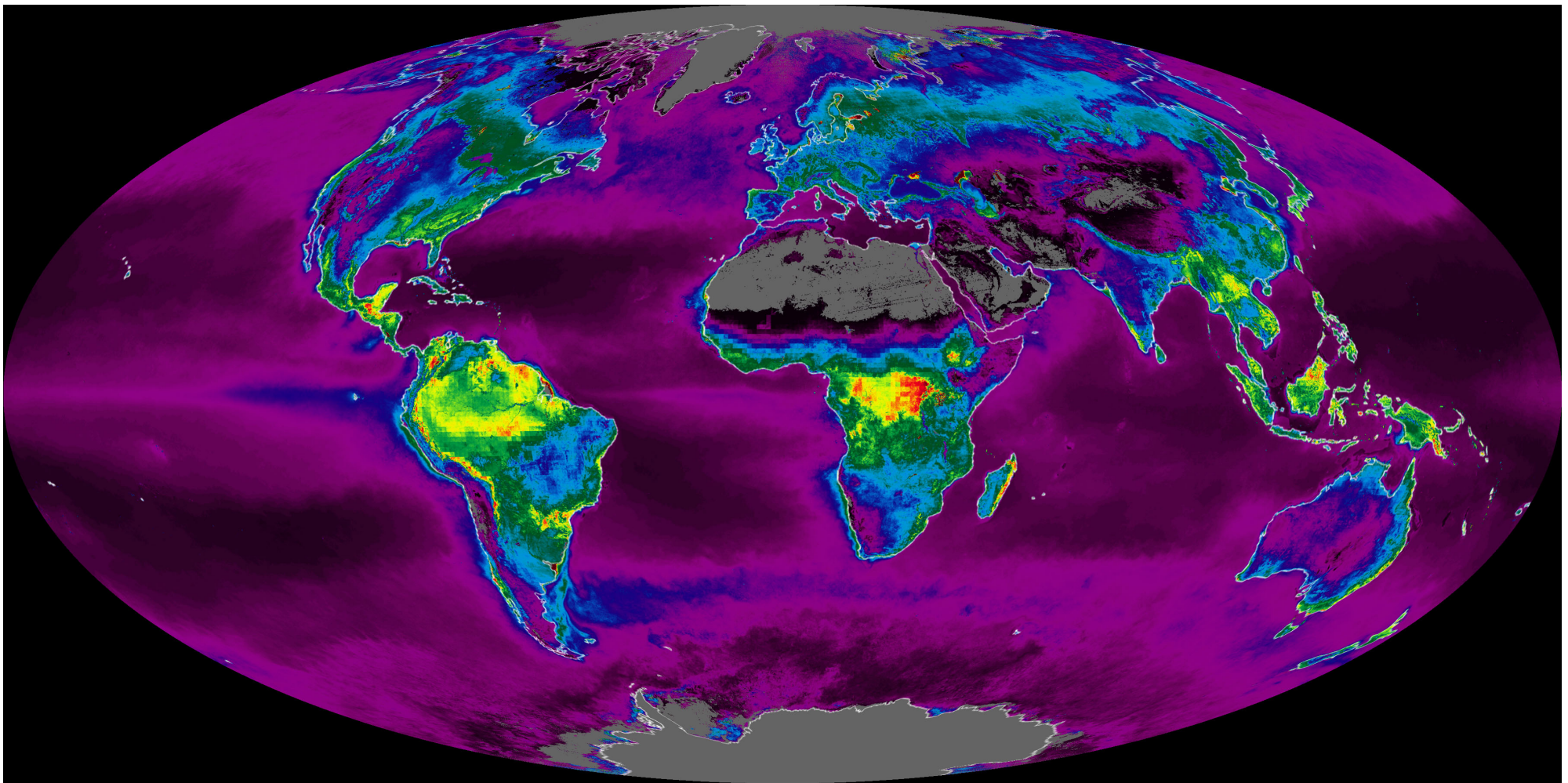
Gross primary **production** (GPP): **rate** of conversion of  $\text{CO}_2$  to organic carbon ( $\text{g C a}^{-1}$ ).

Gross primary **productivity**: **rate** of conversion of  $\text{CO}_2$  to organic carbon **per unit surface area** ( $\text{g C m}^{-2} \text{a}^{-1}$ ).

Respiration by autotrophs ( $R_A$ ) = how much carbon ( $\text{g C a}^{-1}$ ) is used for plant metabolism.

Net primary production (NPP) =  $GPP - R_A$  = how much carbon ( $\text{g C a}^{-1}$ ) is stored as biomass.





Net Primary Productivity (kgC/m<sup>2</sup>/year)



Moderate Resolution Imaging Spectroradiometer (MODIS)